USDA

ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

1998

U.S. Water Conservation Laboratory

WATER SAVED IS WATER EARNED

Phoenix, Arizona

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

1998

U.S. WATER CONSERVATION LABORATORY
U.S. Department of Agriculture
Agricultural Research Service
4331 E. Broadway Road
Phoenix, Arizona 85040

Telephone: (602) 379-4356
FAX: (602) 379-4355
E-mail: bclemmens@uswcl.ars.ag.gov
Website: www.uswcl.ars.ag.gov

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INTRODUCTION

1998 was a year of significant change at the U.S. Water Conservation Laboratory. We were saddened by the departure of Al Dedrick after 25 years at the laboratory, the last 8 as director. At the same time, we are pleased that he is now serving as Associate Deputy Administrator for Natural Resources and Sustainable Agricultural Systems at ARS Headquarters in Beltsville, Maryland. We know that ARS will benefit immensely from having Al in that position. Bruce Kimball stepped in as acting director for the first half of the year and did an admirable job of keeping us on course.

Over the past few years, Al Dedrick motivated us to get in closer touch with our clients and customers. This perspective will help us greatly in planning our research for the future. Al has also brought this focus to the National Program Staff, where we are seeing major changes in the way ARS organizes its research programs. We believe that the result will be more cooperation, both within and outside of ARS, and more relevant research here at the U.S. Water Conservation Lab.

Bob Rice retired at the end of September after almost 40 years at the laboratory. He was hired upon graduation from Colorado State University and was one of the first scientists at the laboratory back in 1959. We wish him and his wife Jo Ann well.

Lloyd Myers, the laboratory's first director, died on December 21, 1998. We owe a debt of gratitude to Lloyd for establishing the laboratory's tradition of excellence. Lloyd instituted an open, cooperative, enthusiastic atmosphere that persists today and makes this laboratory an excellent place to work. We thank him.

Water conservation is an immense challenge. It is so broad and so critical to society both here and abroad that the opportunities for positively impacting both science and practice are almost limitless. With our present funding and staff, we are able to tackle only a few aspects of this problem. However, the laboratory should be proud of its long history of producing meaningful and useful research results. Our job is to identify those areas of research that are most critical to the long-term sustainability and enhancement of modern society. While water is a renewable natural resource, it is also a limited one, and one upon which the entire planet depends for its survival.

In the last century, once abundant water resources have become over-allocated by an ever growing population. We can only imagine the critical water problems we will face if this trend continues for another century. But whatever that scenario, science will play a key role in helping society find the appropriate balance between the environment and human needs. That is our challenge.

Bert

Bert Clemmens
Director

DEDICATION

Allen R. (Al) Dedrick's 38-year professional career with ARS, almost all in research as an agricultural engineer, has been characterized by his clear recognition that he and his colleagues were there to serve the farm and the farmers, not vice versa. When his field crews commented on the pre-dawn start times, his response was that if you're going to work with farmers, you work when they do. An iron-clad rule will be remembered from his leadership of a cooperative project with farmers and a number of agencies: "You don't have a meeting without a farmer in the room."

Al grew up on a farm near Red Cloud, Nebraska, and started in ARS as a student trainee in Lincoln, Nebraska, in 1958. He moved to Logan, Utah, in 1967 where he received his Ph.D. from Utah State; thence to Phoenix, Arizona, in 1973; and Beltsville, Maryland, in early 1998. The 25 years in Phoenix were spent here at the U. S. Water Conservation Laboratory. He served as director from 1990 until 1998 when he was appointed Associate Deputy Administrator for Natural Resources and Sustainable Agricultural Systems, USDA-ARS National Program Staff. Al's appointment to oversee ARS research in natural resources was particularly appropriate. He often voices concern that the natural resource base that provides the Nation's (and the world's) food and fiber is "once removed" from public awareness and advocacy.

Al's leadership of the U.S. Water Conservation Laboratory was marked by continuing research achievement, organizational streamlining, mentoring of younger scientists for research and leadership roles, and outreach to inform and receive guidance from users of the laboratory's research.

His approach to research has been uniquely holistic, from on-farm systems to large water project delivery systems and the heretofore overlooked critical interface between farm and delivery systems. His work has included erosion control; water harvesting methods; seepage and evaporation control; irrigation engineering, including level-basin irrigation and automatic control; and irrigation system performance, operation, and management. Those who have asked Al to review technical papers will attest to the insightfulness and thoroughness of his critiques. Some say that they preserve the marked up copies for humility when they become famous. But whatever his role--critic, colleague, mentor, or some combination--it was infused with optimism and encouragement.

In addition to his research both in the U.S. and overseas, Al has served his profession in many roles, often in leadership positions. He is nearing two decades as a U.S. delegate to the International Standards Organization, and in 1989, he was named "Man-of-the-Year" by the Irrigation Association for contributions to irrigation by an individual outside the industry.

We dedicate the 1998 Annual Research Report to Al for his leadership and service on behalf of the U.S. Water Conservation Laboratory. As he continues his career with ARS, we wish him the best. And in his personal life, may every lake he fishes abound in hungry 10-pound largemouth bass; may the Nebraska football team be perennially #1; and may Al have many healthy years to enjoy both!

Laboratory Program

HISTORY

The U.S. Water Conservation Laboratory is part of the Agricultural Research Service (ARS), the major research arm of the U. S. Department of Agriculture. The primary mission of ARS is to help meet the nation's food and fiber needs. ARS works closely with the State Experiment Stations, State Departments of Agriculture, other government agencies, public organizations, farmers, ranchers, and industry. The organizational structure of ARS is designed to insure active research programs and to provide maximum responsiveness to the needs and problems of the public.

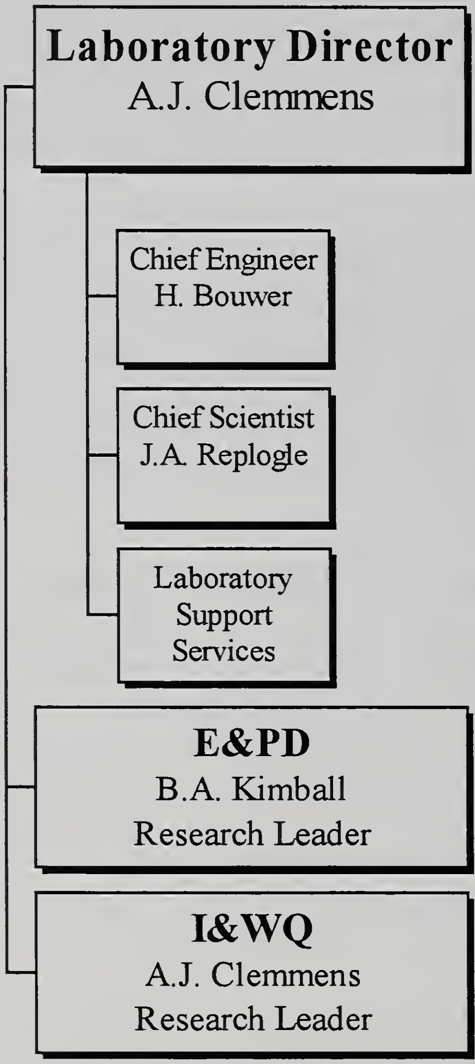
The U. S. Water Conservation Laboratory was established in central Arizona in 1959 to develop methods to conserve surface and groundwater used for agriculture. Research focuses on more efficient use of water and reduction of water losses in the soil-plant-atmosphere continuum. More recently, research has expanded to include studies in water quality, new crops with low water requirements, and effects of increased carbon dioxide on crop production, water use, and climate. The research is national in scope with international impact and deals with both present and potential problems. Although research results are documented primarily in technical literature, the staff works directly with State and Federal agencies.

In addition, the staff works closely with industry and individuals to facilitate technology transfer. New concepts and prototype equipment are tested cooperatively under actual conditions. The Laboratory does both theoretical and applied research at field sites and in laboratories. Facilities are well equipped for these purposes. Specialized electronic and mechanical prototype equipment is made in-house. Basic equipment to support the research programs includes electronic instrument calibration apparatus, data acquisition and processing computers, controlled environmental rooms, sophisticated water flow calibration, control and measuring devices, and a spectral imaging analyzer system. Specialized laboratory analytical instruments consist of a mass spectrometer, gas and high performance liquid chromatographs, automated titrator, solution analyzer, infrared gas analyzer, electropheretic equipment, and cytological microscope.

The research teams are composed of engineers and scientists trained in various disciplines. The disciplines represented are civil, agricultural, and hydraulic engineering; soil and biological sciences; physics; chemistry; and plant physiology and genetics. Support staff consists of agricultural, biological, and physical science technicians, an electronics engineer, a computer systems manager, a program analyst and a machinist. Administrative support includes secretaries, clerks, and maintenance personnel.

The total Laboratory research effort operates under two research groups that work closely in a multi-disciplinary, cooperative manner: the Irrigation and Water Quality (I&WQ) and the Environmental and Plant Dynamics (E&PD) Research Units.

Laboratory Organization



Mission

The mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing better methods for scheduling irrigations, developing the use of remote sensing techniques and technology, protecting groundwater from agricultural chemicals, commercializing new industrial crops, and predicting the effect of future increases of atmospheric CO_2 on climate and on yields and water requirements of agricultural crops.

LABORATORY MANAGEMENT

ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow; surface water-groundwater relations.

JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

BRUCE A. KIMBALL, B.S., M.S., Ph.D., Research Leader for Environmental and Plant Dynamics and Supervisory Soil Scientist
Effects of increasing atmospheric CO_2 and changing climate variables on crop growth and water use; free-air CO_2 enrichment (FACE) and CO_2 open-top chambers and greenhouses; micrometeorology and energy balance; plant growth modeling.

LABORATORY SUPPORT SERVICES

ELECTRONICS ENGINEERING LABORATORY

D.E. Pettit, Electronics Engineer

The electronics engineering laboratory is staffed by an electronics engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U.S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase, and upgrade of electronic equipment. Following are examples of work orders performed in 1998:

- Continued to design the Generation 2 probes, inverting switching regulator positive and negative DC power modules, and water flow monitoring power interlock device.
- Modified Generation 2 probe software.
- Repaired and modified a variety of equipment throughout the year, including CR21X data loggers and CR7 data loggers, various hand-held guns, polycorders and polycorder cables, the anemometers, A CO_2 controller system, and A CO_2-IR analyzer unit, CP units, neutron hydro probes, LICOR leaf area machine, multimeters, insect feeding monitor, tone generator and phone base units.
- Constructed 50 new Generation 2 probes, 8 new interface probes between polycorders and neutron hydro probes.

LIBRARY AND PUBLICATIONS

S.D. Gardner, Publications Clerk

Library and publications functions, performed by one publications clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers, as well as for holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 2100 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U.S. Water Conservation Laboratory List of Publications, containing over 2000 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications and is now accessible on LAN by the Research Staff. Publications lists and most of the publications listed therein are available on request.

COMPUTER FACILITY

T.A. Mills, Computer Specialist

The computer facility is staffed by one full-time Computer Specialist and one Computer Assistant. Support is provided to all Laboratory and Location Administration Office computer equipment and

applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining the Laboratory's Local and Wide Area Networks (LAN, WAN), computers, and peripherals. The LAN consist of multiple segments of 10 Base-T, 100 Base-T hubs and one 100VG hub. The LAN is segmented using a high speed switching hub. Segments are made up of CAT 3, CAT 5 and standard Ethernet. This configuration currently provides over 200 ports to six Laboratory buildings. A local router and a 56kbs lease line connects our Laboratory to Arizona State University. ASU provides our LAN access to the WESTNET WAN and the Internet. The Laboratory maintains a Class C block of Internet addresses operating under the domain uswcl.ars.ag.gov. The Laboratory LAN is comprised of seven servers operating under UNIX, Netware 3.12, or Windows NT 4.0. End users operate mainly under Windows 95 with a few OS/2 and Windows NT workstations. Services such as E-Mail, print, file, remote access, and backup are provided by the LAN. The Laboratory maintains its own Web Server, which can be accessed at www.uswcl.ars.ag.gov.

This year the Laboratory will add its first fiber optic backbone segment continuing its migration to a 100Base-T LAN. The Year 2000 issue is being addressed for all hardware and software. WAN link hardware (router and DSU/CSU's) will be replaced and/or upgraded this year with Year 2000 compliant equipment.

MACHINE SHOP

C.L. Lewis, Machinist

The machine shop, staffed by a machinist and contracted assistant, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U.S. Water Conservation Laboratory research projects. The following are examples of work orders completed in 1998:

A bracket was fabricated for use as part of the Pilot-Static Tube System to measure irrigation well discharge. The bracket was constructed of three pieces of 6061-T6 aluminum. The bracket base piece was cut and machined from 1"x 1" aluminum bar stock to a length of 5.360" +/- .002" with a 1.400"x.476" +/- .002" tongue on one end. Attachment holes were drilled and tapped for 3/8" set screws .5625" and 1.250" from the solid end of the bracket. Two holes, one for clearance and one drilled and tapped for 1/4"-20 thumb screws, were drilled at 90° from the attachment holes 1.875" and 3.275" from the solid end of the bracket. Two holes, one for clearance and one drilled and tapped for 1/4"-20 thumb screws were drilled through the tongue end of the bracket at .3128" and 1.160". A 3/8" ball mill was used to cut a channel .175"+/-.002" deep across the tongue, .800"+/-.002" from the end. A mounting bracket was cut and milled to 1.365"x1.000"x.470"+/-.002". Two holes, one for clearance and one drilled and tapped for 1/4"-20 thumb screws, were drilled into the mounting bracket, one hole at .1828" from the end the other hole at 1.055" from the end. A 3/8" ball mill was used to mill a channel .138"+/-.002" deep across the mounting bracket .5025" from the tapped hole. The second mounting bracket was cut and milled to 1.680"x1.000"x.475" +/-.002". Two holes, one for clearance and one drilled and tapped for 1/4"-20 thumb screws, were drilled at .055"+/-.002" from each end of the bracket. A ball mill was used to mill a channel .350"+/-.002" deep across the bracket .840"from the end.

Sixteen sets of pipe racks were fabricated to transport and store 12-inch PVC pipe used by the FACE experiment. Each rack set consists of a base constructed of two 50-inch 4x4 wood studs with three 2x4 wood stud cross pieces 60 inches long and attached to the 4x4 pieces with 2½-inch wood screws. Four 2x4x19 $^{3}/_{4}$ inch pieces were attached to the 4x4 pieces between the 2x4x60 inch studs using 2½-inch wood screws. The end and center pipe supports were fabricated by ripping 20 foot 4x4 studs at 45° angles. The angle cut pieces were then cut into 3 ½ inch lengths and attached to the base using 2-inch wood screws. Three sets of rack spacers were then fabricated from 2x4 wood studs cut to 50-inch lengths with end and center pipe supports attached to both sides using 2-inch wood screws. Each set of racks was then treated with Thompson's water sealer.

Fifty timer boxes used in the fabrication of opportunity timers for the Irrigated Farm Management Project were modified for further assembly purposes. A fixture was first fabricated to provide a precision start point for all milling operations. The box lids were then modified by milling openings in the long ends. Each end was milled on three surfaces. The box bases were modified by milling openings in the long ends. The closed end was milled on 5 surfaces and the open end of the box was milled on 9 surfaces. All milling operations were run with tolerances of +/- .002".

A Psycrometer Input Panel was fabricated for use in the FACE experiment. The panel was fabricated in two pieces of 1/4" plate 6061-T6 aluminum. The panel was cut and milled to 20.000"x 17.000"+/- .002". Seventy-two 1/2" through holes were then drilled c/c 1.750". Two hundred and eighty-eight holes were drilled and tapped for 2-56 pan head machine screws. These holes were drilled at four points equidistant around the 1/2" holes with a tolerance of +/- .002". A base plate was cut and milled to 6.250"x 17.000"+/- .002". The base plate was welded to the panel at 80 degrees. The weld was then ground to surface levels, and the entire unit was sandblasted to a matte finish.

USWCL OUTREACH ACTIVITIES

During 1998, the USWCL staff participated in numerous activities to inform the public about ARS and USWCL research, to solicit input to help guide the USWCL research program, to foster cooperative research, and to promote careers in science. A summary of those activities follows:

Annual Research Program Planning Meeting, January 12. Participants included 42 "users" and representatives from consulting firms; commercial enterprises; federal, state, and county agencies; universities, the ARS National Program Staff; and other ARS locations. Most of the day was spent in facilitated breakout groups representing the five USWCL research areas. Participant packages, containing an overview of the meeting and summary of visitor input and group discussions, were later provided to visitors, ARS management, and other ARS locations.

McKimmey Middle School Earth Day, April 21. USWCL provided an exhibit. Among the handouts, over 100 copies of "Science in Your Shopping Cart" were distributed.

Agricultural Summer Institute, June 22. USWCL conducted a session of this one-week institute, which was attended by thirty-two junior and senior high school teachers from across Arizona.

"Experiments for the Classroom." The USWCL web site contains experiments suitable for high school science classes.

Northern Arizona University Plant Biology Class Visit. About three times a year, the New Crops program hosts a Plant Biology class from the Northern Arizona University continuing education program in Flagstaff, Arizona. Gail Dahlquist, Agricultural Science Research Technician (Plants), organizes the visits.

Student Participation in New Crops Program. Four students from the Carl Hayden High School Agricultural Biotechnology program in Tempe, Arizona, worked with the New Crops program. All had separate projects, and all received an outside award and/or college scholarship for their work.

Student Science Fair Projects. Terry Coffelt, Research Geneticist, assisted two students with science fair projects.

"Poor Man's Biosphere." Sherwood Idso took his "poor man's biosphere" approach to global change experimentation to three local schools where it was tested successfully in an honors botany high school class, an eighth-grade general science class, and a fifth-grade class at an elementary school of the Salt River Pima-Maricopa Indian Community. At the high school, the experimental program was the basis for the honors botany class entry in a statewide science project competition that won the participants first place in the state and a $10,000 award for science enrichment activities. The project was deemed so outstanding with respect to all other

entrants that the judges refused to award any second or third place prizes! Work is in progress to make the experimental program available to teachers and students worldwide via scientific and educational publications and programs.

Science and Engineering Exposition, October 6, 1998. The U.S. Water Conservation Laboratory and the Maricopa County 4-H held its annual Science and Engineering Exposition (SEE), to which Junior and senior high teachers are encouraged to bring their classes to participate in "hands-on" demonstrations. The goal of See is to excite and motivate students about careers in science and engineering. SEE featured nine stops on a tour of demonstrations, or mini-experiments, designed to have the students actively participate and suggest how the problems presented might be solved. To assist teachers in incorporating the information presented at the Exposition into the curriculum, study guides are sent to each class about two weeks prior to the event.

ARS Irrigation and Drainage Exhibit at the International Irrigation Show. USWCL coordinated an ARS exhibit on irrigation and drainage (I&D) research at the annual Irrigation Association International Exposition, November 1-3, in San Diego, CA. The exhibit was titled "Irrigation and Drainage in Harmony with the Environment" and featured the on-line version of the "Directory of ARS I&D Researchers and Research" on the ARS web site. Besides the directory, visitors were able to visit other web sites on the ARS home page and at ARS locations. The registered attendance of the Expo was about 7000, and the ARS exhibit was well attended. Several hundred copies of "Science in Your Shopping Cart" were distributed along with copies of *Agricultural Research* magazine. The Irrigation Association provided complimentary exhibit space, and the exhibit was otherwise supported by Dale Bucks, National Program Leader for Water Quality and Water Management. The exhibit booth was staffed by I&D researchers from ARS locations at Phoenix, Arizona; Fresno, California; Florence, South Carolina; and Lincoln, Nebraska.

SAFETY

G. McDonnell, J. Askins, and K. Johnson

The Laboratory Safety Committee enjoys well-deserved respect from the employees. The committee takes its duties seriously and has worked diligently to insure compliance with all EPA and OSHA regulations and radiological safety protocols. Employees are encouraged to report all safety concerns, even those that might seem trivial.

In addition to several standing committee members, six other members serve three year terms, with two members rotating off each year. Current committee members are Terry Coffelt, Doug Hunsaker, Paulina Harner, Brian Wahlin, Stacy Richards, and Stephanie Johnson, rotating members; Bud Lewis (shop), Francis Nakayama (radiological/chemical), and John Replogle (hydraulics lab), standing members.

It is a time-consuming commitment, and requires judicious management of time and work priorities. Serving on the safety committee, however, is gratifying in terms of its record of accomplishments. Following are some of the results of the committee's efforts in1998:

- The annual safety fair has grown into a week-long series of activities, drawing attendees from a number of locations nationwide. A great deal of credit is due Dixie Albright, Location Safety and Occupational Health Manager, for the scope and impact of this activity.
- A chemical inventory data base was developed that provides all the published information employees would need on a given chemical.
- The hazardous waste marshaling area for the location, which includes the USWCL and the Western Cotton Research Laboratory next door, was brought into compliance with EPA regulations.

The Lab staff thanks the committee for their good work on our behalf.

STUDENTS AT USWCL

J. Askins

The USWCL has enjoyed a mutually beneficial relationship with students from nearby Arizona State University over the years. Students come under workstudy agreements and student federal appointments. They perform a variety of tasks, from collecting samples to solving computer problems; from numbering vials to writing protocols; from weighing soil to processing and analyzing non-soil data. Students who work in the clerical/administrative area have worked in personnel and safety areas as well as doing general clerical work such as filing and copying. Operation of ARS automated systems, publication clerk duties, and literature searches are also performed.

The students benefit from the income and experience, and we benefit from their enthusiasm, up-to-date expertise, and energy. Some have stayed on after graduation, even earning PhDs under ARS assistance programs.

I&WQ Management Unit

I&WQ Organization

IRRIGATION & WATER QUALITY
A. J. Clemmens
Research Leader

- **WATER PROJECT MANAGEMENT**
  - E. Bautista, Agricultural Engineer
  - H. Bouwer, Research Hyd. Engineer
  - A. J. Clemmens, Research Hyd. Engineer
  - J. A. Replogle, Research Hyd. Engineer
  - B. T. Wahlin, Civil Engineer
- **IRRIGATED FARM MANAGEMENT**
  - F. J. Adamsen, Soil Scientist
  - W. L. Alexander, Agronomist
  - A. J. Clemmens, Research Hyd. Engineer
  - D. J. Hunsaker, Agricultural Engineer
  - T. S. Strelkoff, Research Hyd. Engineer

Mission

The mission of the Irrigation and Water Quality Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit addresses high priority research needs for ARS's National Programs in the area of Natural Resources & Sustainable Agricultural Systems. The unit primarily addresses the Water Quality and Management National Program. It also addresses the application of advanced technology to irrigated agriculture.

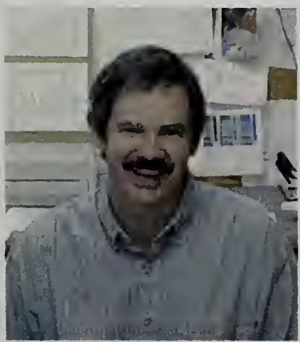
I&WQ RESEARCH STAFF

FLOYD J. ADAMSEN, B.S., M.S., Ph.D., Soil Scientist
Management practices that reduce nitrate contamination of groundwater while maintaining crop productivity; application of 100% irrigation efficiency; winter crops for the irrigated Southwest that can be double-cropped with cotton; contributions of natural and urban systems to nitrate in groundwater.

WILLIAM L. ALEXANDER, B.S., M.S., Agronomist
Drip and sprinkler irrigation systems; flood irrigation on field crops; all aspects of vegetable crops, particularly drip irrigation, chemigation, and pest control.

EDUARDO BAUTISTA, B.S., M.S., Ph.D., Agricultural Engineer
On-farm irrigation system hydraulic modeling; hydraulic modeling of irrigation delivery and distribution systems; control systems for delivery and distribution systems; effect of the performance of water delivery and distribution systems on-farm water management practices and water use efficiency; integrated resource management and organizational development for irrigated agricultural systems.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow, surface water-groundwater relations.



ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

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DOUGLAS J. HUNSAKER, B.S., M.S., Ph.D., Agricultural Engineer
Effects of soil and irrigation spatial variability on crop water use and yield in large irrigated fields; level basin irrigation design and management procedures for applying light, frequent water applications to cotton; CO2 effects, in particular, of evapotranspiration in the free-air CO2 enrichment (FACE) environment; evaluation of water requirements and irrigation management of new industrial crops--lesquerella and vernonia.

JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

THEODOR S. STRELKOFF, B.C.E., M.S., Ph.D., Research Hydraulic Engineer
Surface-irrigation modeling: borders, furrows, two-dimensional basins; erosion and deposition; design and management of surface-irrigation systems; canal-control hydraulics; flood-routing methodologies; dam-break floodwaves; flow in hydraulic structures.

BRIAN T. WAHLIN, B.S., M.S., Civil Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

IRRIGATED FARM MANAGEMENT ANALYTICAL LABORATORY

K. Johnson, S. Colbert, and J. Askins, Physical Science Technicians

Following is a description of the functions of the Irrigated Farm Management (IFM) Analytical Laboratory. The IFM Lab is staffed by the three physical science technicians listed above.

High performance liquid chromatography (HPLC) is used to analyze nitrate and other anions in soil samples. The computer was given network capability for future backup facilitation and data access. Methods for data aquisition were revised as the detector was changed and as different ions were to be analyzed.

The autoanalyzer, a system utilizing colorimetry to determine nitrate and ammonia content of water samples and extracts of soil samples, was run and maintained. The need to dispose a hazardous substance, cadmium, in a coil used by the instrument, was discovered and addressed. The software has been updated to a more powerful Windows based system.

The laboratory has been determining total elemental carbon and nitrogen from soil samples for many years. The system was upgraded in 1997 to include the analysis of C^{13} and N^{15} on the isotope ratio mass spectrometer. Samples also have been run on this machine for groups other than IFM. New software required development of a new protocol. Fine-tuning of the instrumentation required much research and telephone assistance from the company that manufactured the instrument and created the software.

In addition to running and maintaining instruments, research technicians process data and address the precision of the data. Good precision testing alerts the operator to the necessity of a rerun and informs scientists of data reliability. Technicians also weigh soil samples, collect samples in the field, help with irrigation and other field work, write and update protocols for both reference and training, count seeds, and perform numerous other duties as needed. Combining and summarizing data from HPLC, autoanalyzer, and weighings were expedited by creating macros in a spreadsheet. One of the technicians will be sent for training in running the atomic absorption spectrometer, soon to be moved into this laboratory.

A short term goal is to have data from the weighing and the instrumental analyses as well as their summary available electronically, and progress has been made in this direction.

IRRIGATED FARM MANAGEMENT

CONTENTS

IRRIGATED FARM MANAGEMENT

MISSION

To develop irrigation farm management systems for arid zones that integrate year-round crop rotational strategies with best management practices (BMPs) for water, fertilizer and other agricultural chemicals. These systems will be environmentally sustainable, protect groundwater quality, and be economically viable.

STUDIES ON CONSUMPTIVE USE AND IRRIGATION EFFICIENCY

D.J. Hunsaker, Agricultural Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Effective irrigation management provides the timely and correct amount of water consistent with the crop water demands, soil conditions, crop production goals, and environmental quality goals. Irrigation efficiency (IE) is a term often used to describe the effectiveness of irrigation, where IE is defined as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied. Beneficial uses include crop evapotranspiration ($ET_{c)}$, salt leaching, frost protection, etc. General measures that can be taken to improve surface irrigation efficiencies include increasing the uniformity of the water applied, reducing deep percolation and surface runoff, and improving the control of application depths. However, proper irrigation management is a vital requirement for attaining the optimum irrigation efficiency of the system. Thus, the ability to predict actual daily crop water consumption, or ET_c, is of major importance.

A practical, and widely used method for estimating actual ET_c is the crop coefficient approach, which involves calculating a reference crop (ET) with climatic data: ET_c can then be determined by multiplying the reference ET with an appropriate crop coefficient (K_c). The Food and Agricultural Organization (FAO)-24 publication on *Crop Water Requirements* has been used worldwide as a primary source for crop coefficients and related procedures. Recently, the international committee revising the FAO-24 publication has developed new procedures and guidelines for estimating crop coefficients. These include a new procedure known as the "basal crop coefficient" approach. Here, the crop coefficient ($K_{c)}$ is determined on a daily basis as the summation of two terms: the basal crop coefficient (K_{cb}) and the contribution of evaporation from wet soil surfaces following irrigations or rain (K_e). When the soil surface is dry, K_c is equal to K_{cb}, assuming soil moisture is adequate to sustain full crop water use. The usefulness of the basal crop coefficient approach is that it provides better estimates of day to day variations in soil surface wetness and the resulting impacts of irrigation frequency on daily crop water use. To use the K_{cb} approach, several parameters need to be measured or estimated. These include values for the maximum depth of cumulative soil evaporation from the surface at the end of stage 1 and stage 2 drying cycles for soils in the area, the fractional area of soil surface covered by vegetation during the growing season, and fractional wetted area of the soil by the particular irrigation system.

In the early 1980s, the U.S. Water Conservation Laboratory (USWCL) released a publication that presented daily, semimonthly, and seasonal consumptive water use estimates for a number of commercial crops grown in this region. The consumptive use information for the crops were average values based on several years of data developed in studies conducted 20 or more years ago. The effects of soil evaporation were not included in the estimates of consumptive use and climatic data from the studies were limited. These shortcomings curtail the use of the early consumptive use, data for application in the basal crop coefficient approach. Quantifying the contribution of wet-soil evaporation is particularly important since soil evaporation in excess of basal ET is sometimes included in ET_c as a beneficial use and sometimes it is not. Nevertheless, the early data have been useful for assisting on-farm irrigation management and, in some cases, for determining irrigation

project planning, state water duties, and water right transfers.

Recently, several different entities have approached the USWCL interested in new information on consumptive use of crops in the area. A particular concern is the realization that many farmers have been unable to meet a target irrigation efficiency of 85%. The objective of this project is to determine the consumptive use and attainable irrigation efficiencies for crops presently produced, as well as for several new industrial crops that are being developed in the region.

APPROACH: Research is being conducted through a series of field experiments to determine crop evapotranspiration (ET_c) for current varieties of cotton, wheat, alfalfa, rape, lesquerella, and guayule grown under irrigation and soil conditions common in the region. Crop ET during different growth stages in the season will be measured primarily with a soil water balance using neutron probes and time-domain-reflectometry (TDR), although other methods such as sap flow gauges and lysimeters may also be used when possible. Basal crop coefficients (K_{cb}) will be developed from the ET_c data using the revised FAO-24 basal crop coefficient procedures and local meteorological data, including the grass-reference evapotranspiration (ET_o), provided by the Arizona Meteorological Network's weather stations. Figure 1 illustrates K_{cb} values derived from measured ET_c data for cotton in 1993, and the resultant K_{cb} and K_c ($=K_{cb}+K_e$) curves that were developed using the FAO-24 procedure. The lower frame in figure1 shows the actual irrigation and rainfall amounts applied to the cotton. For each crop, K_{cb} values derived from different experiments will be combined and used to develop crop coefficient curves as a function of common time-based indexes, e.g., days past planting and cumulative growing degree days. Figure 2 shows the K_{cb} curve as a function of growing degree days that was developed from two years of data for cotton. The crop coefficient curves, such as that in figure 2, will be tested to determine their effectiveness in

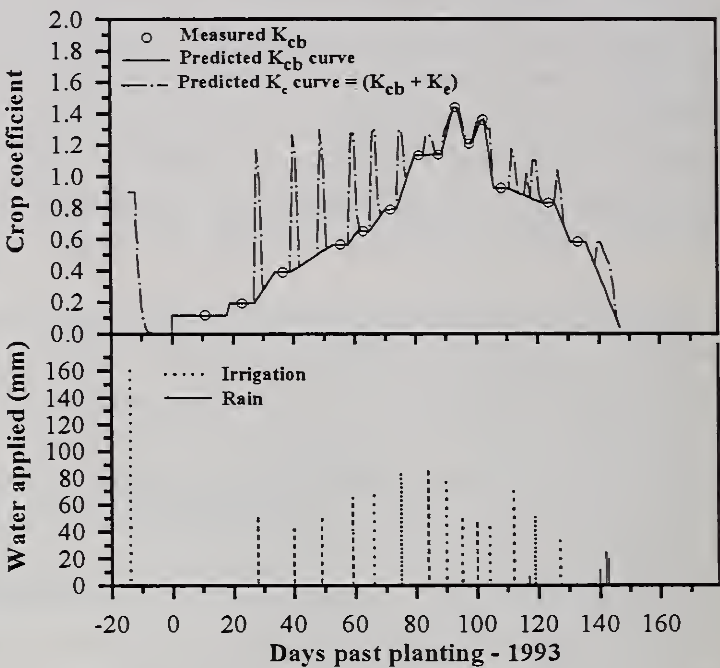


Figure 1. K_{cb} values and crop coefficient curves.

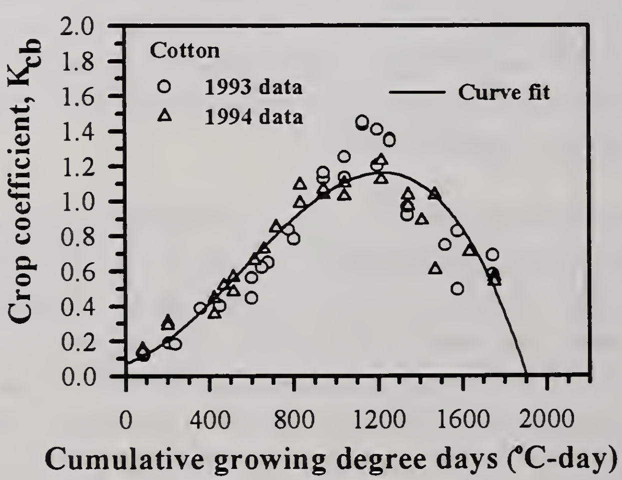


Figure 2. K_{cb} curve for cotton.

predicting ET_c for different fields and years.

Using the crop coefficient curves within the revised FAO-24 procedure, estimates of crop ET and soil evaporation can be made on a daily basis. This provides the ability to determine irrigation efficiencies on a single irrigation basis, as well as for the entire season. Irrigation efficiencies will be examined for cotton from small basin studies and studies undertaken on a cooperating grower's field in the next section.

FINDINGS: Table 1 summarizes the water use for a short-season cotton cultivar grown in small basins under two different irrigation frequency treatments, high-frequency (H) and low-frequency (LHL) in 1993 and 1994.

Table 1. Seasonal cotton ET_c, soil evaporation, and irrigation and rainfall applied for two irrigation frequency treatments in 1993 and 1994.

	1993 Treatments		1994 Treatments	
	H	LHL	H	LHL
ET_c (mm)	820	819	811	770
Soil evap. (mm)	130	94	149	125
Total ET_c plus soil evap.(mm)	950	913	960	895
Irrigation (mm)	993	986	995	992
Rainfall (mm)	60	60	77	77
Total water applied (mm)	1053	1046	1072	1069

The amount of water consumed strictly as crop ET_c for the H (15 irrigations) and LHL (12 irrigations) treatments was similar for the treatments in 1993, but somewhat higher for the H than LHL in 1994. Higher soil evaporation occurred for the H treatment, due to more frequent irrigations. The amount of soil evaporation represented 14 and 16% of the total crop water use for the H, and 10 to 14% for the LHL treatments in 1993 and 1994, respectively. The irrigation efficiency (IE) calculated for the treatments varied from 90 to 96% when soil evaporation was included as beneficial water use, but 78 to 83% when it was not.

Table 2 presents seasonal irrigation efficiencies attained during four years in 490-m long, sloping borders on a commercial cotton field. When based on the total water delivered, IE varied from 59 to 65% over the four years. However, even when the loss of delivered water to runoff was excluded (e.g., as if it were recovered for reuse), irrigation efficiencies were still low (72 to 77%).

Table 2. IE based on water delivered and average depth infiltrated for cotton in grower's field.

Year	Water delivered (mm)	Average depth of water infiltrated (mm)	Total ET† (mm)	ET/delivered (%)	ET/infiltrated (%)
1994	1760	1410	1040	59	74
1995	1750	1400	1080	62	77
1996	1560	1370	1010	65	74
1997	1660	1440	1030	62	72

† Includes soil evaporation

Evaluation of single irrigations for the commercial field indicated that large inefficiencies occurred during early season irrigations when crop ET was small.

INTERPRETATION: Findings from these preliminary evaluations indicate that evaporative water losses from the soil need to be considered in determining crop water use and irrigation efficiencies. Even in carefully controlled small basins, irrigation efficiencies above 85% were not achieved when soil evaporation was not considered. As evidenced by the case study, farmers have difficulties achieving an 85% irrigation efficiency even when soil evaporation is considered. For large commercial fields, irrigation applications need to be more carefully managed to match crop water demands. Information for more accurate crop ET prediction will be developed in this project. However, field spatial variability or inadequate irrigation design in large fields may preclude smaller irrigation applications.

FUTURE PLANS: In addition to developing basal crop coefficient curves for crops, studies will be developed more accurately to assess soil and crop parameters used for various components in the revised FAO-24 procedures. These include determining the maximum depths of cumulative soil evaporation from the surface at the end of stage 1 and stage 2 drying cycles for soils in the area, the fractional area of soil surface covered by vegetation during the growing season, and fractional wetted area of the soil by various irrigation systems.

COOPERATORS: Rick Allen, Professor, Utah State University; Ed Martin, Irrigation Specialist, The University of Arizona; Huanjie Cai, Professor, Northwest Agriculture University, Yangling, Shaanxi, China.

EVALUATION OF YEAR ROUND CROP ROTATIONS TO IMPROVE NITROGEN AND WATER MANAGEMENT

F. J. Adamsen, Soil Scientist; D. J. Hunsaker, Agricultural Engineer; and R. C. Rice, Agricultural Engineer

PROBLEM: Formation of nitrate during fallow periods in traditional cotton and alfalfa production systems can lead to leaching of nitrate to groundwater when preplant irrigations and early season irrigations are made. One solution to this problem is keeping these systems in continuous crops, which would shorten or eliminate fallow periods and provide a crop to utilize mineralized nitrogen. Any new rotation system must be economically viable and be logistically possible. In addition, new cropping systems should not require a large investment in new equipment nor should there be major difficulties in learning the cultural aspects of new crops in a system. Several crops which are not currently grown in the area can potentially be used in rotation systems to provide year-round cropping. These include rape, both industrial and Canola types, lesquerella, an industrial oil seed, and guayule, a desert shrub which is a source of latex, rubber and resins. Rape and lesquerella are cool season annuals which can be grown as winter crops. Both can be planted in October or November following cotton. Rape matures in early to mid-April making it suitable as a rotational crop with short-season determinant cotton varieties. Lesquerella matures in June, which is too late in the season to be planted in a rotation with cotton, but it can be grown with a short warm season crop such as sorghum. Guayule can potentially be used in rotation with alfalfa. The objective of the project is to evaluate the effectiveness of several new crop rotation systems in reducing nitrate movement to groundwater and improving overall nitrogen management as well as their economic and agronomic potential.

APPROACH: Research is being conducted through a series of field experiments to evaluate the economic and agronomic viability of four rotation systems on near commercial size fields. The four rotations are 1) continuous full season cotton with winter fallow as a control; 2) industrial rape (cv. R-500) as the winter crop with short season determinant cotton in the summer; 3) lesquerella as the winter crop and sorghum as the summer crop and 4) alfalfa for two years followed by two years of Guayule, both of which are year round crops. Irrigation is high efficiency level basin; plots are 30 by 180 m. Harvestable area of the basins is 30 by 176 m. Cotton is planted on ridges 1 m apart, alfalfa, lesquerella and rape are solid seeded on the flat and sorghum is planted in 0.75 m rows on the flat.

Soil and plant nutrient status are closely monitored. Fertilizer application amounts and timing are based on soil and plant nutrient status. Loading rates of crop residues following harvests of rotational crops are also used in determining fertilizer application timing and amount. For cotton, in addition to the above methods, plant development and boll loads are monitored on a weekly basis to determine fertilizer needs.

Soil water is monitored using a combination of neutron soil moisture meters and time domain reflectance (TDR) methods. Irrigation frequency and amounts are calculated using AZSCHED irrigation scheduling software with feedback from soil moisture determinations. Water amounts are

determined using a flume that is monitored with a double bubbler level recording system to determine the amounts of water applied to each basin. Rate of advance and recession are also recorded for some irrigation events. Yields for each basin are recorded to determine commercial yields, and m^2 areas are harvested for each crop at several locations throughout each basin for each crop to provide an estimate of field variability.

FINDINGS: Alfalfa was planted in early October of 1997 and the first cutting was March 24, 1998 (Table 1). By October of 1998 there were seven cuttings. The highest yields of alfalfa were in spring and early summer, and yields declined during the hottest part of the summer and into fall. Army worms infested the crop in August and reduced yields but harvest caused the worm population to crash and the problem to end.

Lesquerella was planted in October and harvested in June. At flowering in early March, 67 kg ha^{-1} of nitrogen was applied in the irrigation water. Lesquerella yielded 1081 kg ha^{-1} of seed and 10000 kg ha^{-1} of straw. Because of the amount of litter, 200 kg ha^{-1} of N was applied to the following crop of sorghum.

Rape was planted in November of 1997 and harvested in late April of 1998. The crop yielded 1914 kg ha^{-1} of seed and approximately 10000 kg ha^{-1} of straw. Soil nitrogen concentrations were at or near detection limits in the surface soil after harvest. As a result, 200 kg ha^{-1} of nitrogen was applied to the following crop of cotton. Short season determinant type cotton (cv. Deltapine 45 BT) was planted in late-May. Only the preplant N was applied to the short season cotton.

Full season cotton (cv. Deltapine 90 BT) was planted in mid-May. Fifty kg ha^{-1} of N was applied preplant to the full season cotton and additional 125 kg ha^{-1} of N was applied in two applications during the growing season in the irrigation water.

INTERPRETATION: The yield patterns for alfalfa were normal, and overall were quite good. Prices for alfalfa hay dropped during the season which hurt the profitability of the operation. Final production costs still are being determined.

Lesquerella and rape yields were both lower than expected. Rape was not fertilized during the growing season, which may have been a factor in yields. Seeding rate for lesquerella were lower that recommended because of a shortage of seed. Both crops were marketed by the research farm but total production costs are still being determined. However, based on yields, profit margins are expected to be small. Both crops required small inputs in terms of water and nutrients and there were pesticide applications on the rape and one herbicide application on the lesquerella. The major production cost for both of these crops was water.

Crop	Date	Yield, kg ha^{-1}
Alfalfa		
	24-Mar-1998	4523
	29-Apr-1998	4898
	22-May-1998	4391
	4-Jul-1998	4311
	4-Aug-1998	3323
	31-Aug-1998	2540
	3-Oct-1998	2489
Lesquerella		
	Jun-1998	1081
Rape		
	Apr-1998	1914

Table 1. Yields of crops in the rotation study in 1998.

EVALUATION OF RAPE AND CRAMBE AS POTENTIAL WINTER CROPS TO REDUCE NITRATE ACCUMULATION IN THE SOIL

F. J. Adamsen, Soil Scientist; W. L. Alexander, Agronomist; and R. C. Rice, Agricultural Engineer

PROBLEM: Formation of nitrate during fallow periods in irrigated cotton rotation systems can lead to leaching of nitrate to groundwater when preplant irrigations are applied in order to make the soil suitable for tillage operations. One solution to this problem is growing a winter crop that utilizes residual nitrogen and nitrate mineralized during the winter. Due to the cost of water, any crop grown in the winter under irrigated conditions must have an economic return in order to gain producer acceptance, and a crop must be found that can be planted after cotton harvest in the fall and can be harvested before cotton is planted in the spring. Two crops which may meet these restrictions are rape and crambe. Industrial rape and crambe both contain erucic acid, which has industrial potential, and Canola types of rape are valuable as a source of unsaturated cooking oil. Both of these crops are short cool season crops that may meet the short growing season requirement and have a significant nitrogen requirement that would take advantage of residual nitrogen in the soil.

APPROACH: Research is being conducted through a series of field experiments to evaluate yield potential and maturity dates of rape and crambe. One variety of crambe, one variety of spring type industrial rape and eight varieties of spring Canola type of rape were planted in the 1997-1998 growing season in 2 X 12.2 m plots on four planting dates from mid-October to early-December. Row spacing was 0.25 m. The spring industrial, R-500, and three of the spring Canola types of rape, CSU-045, Hyola-029 and Tobin, are campestra types of the species *Brasica rapa* while the other Canola types of rape are from the species *B. napus*. Digital color images were taken weekly of flowers during the flowering period.

FINDINGS: The 5 Nov 1998 planting date had the highest yields for every variety of rape except ST-011 and Tobin, where the 26 Nov 1998 planting date of was highest (Fig. 1). Highest yields of Crambe were from plots planted on 26 Nov 1998. As in 1996-1997, Tobin and to a lesser degree the other *B. Rapa* Canola types had problems with lodging. A more serious problem from a research stand point was bird damage. Early maturing *B. Rapa* varieties in the two earliest planting dates were subject to bird damage because the pods were developed when there were no other sources of food

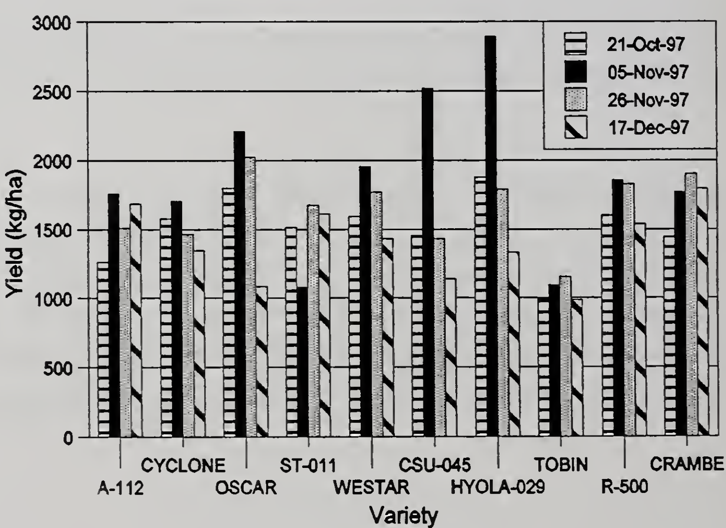


Figure 1. Yield of rape and crambe as affected by date of planting in the 1997-1998 crop year.

available for birds. While this would not be a problem on a commercial scale, the result was extensive loss of production on a small plot basis. Samples were taken prior to harvest and the number of damaged pods determined. Yields were then corrected for the amount of bird damage observed. Losses due to bird damage were as much as 40% for CSU-045. Less than 5% bird damage was observed on the *B. Napus* types and Crambe.

Harvest dates ranged from April 6, 1998 for Tobin in Planting date May 1 to 12, 1998 for Cyclone, Oscar and Westar in planting date 4 (Fig. 2). The *B. rapa* varieties flowered earlier than the *B. napus* types but in general harvest dates were not significantly earlier. Hot weather ended flowering early in planting date 4, which probably lowered yields for the last planting date.

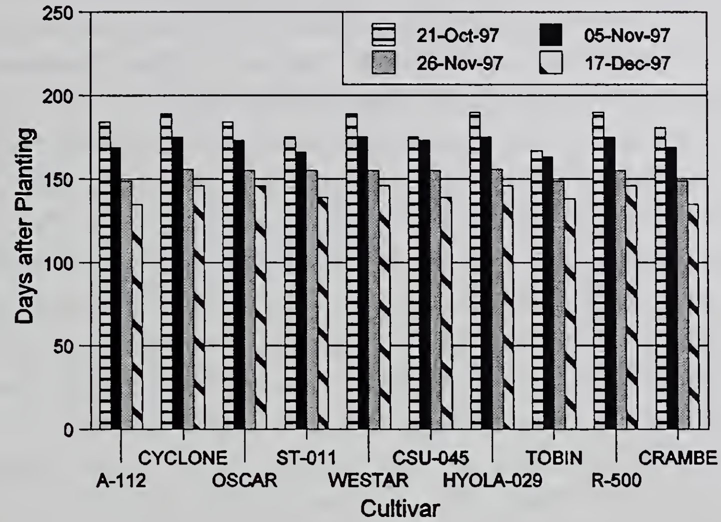


Figure 2. Days after planting of rape and crambe until final harvest as affected by date of planting in the 1997-1998 crop year.

INTERPRETATION: For most of the varieties differences in yield between the first three planting dates were relatively small. The relatively large differences in yield estimates for the second planting date for CSU-045 and Hyola-029 suggest that the correction of the yield for bird damage may have been too large. Yields were lower in 1997-1998 than in previous years although growing conditions appeared normal. Profitable yields need to be at least 2000 kg ha^{-1} which were achieved for only a few cultivars.

Lodging of *B. rapa* varieties continues to be a problem. Tobin, in particular, has shown lodging problems in trials in Colorado and Canada. While bird damage on a commercial field would likely not have a significant impact on yield, in small research plots the effect can be quite large as seen by the corrections made for bird damage to our yield data (Table 1). The timing of pod development of the *B. rapa* varieties in the early planting dates appears to correspond to a period when there is a shortage of food for the bird population. In previous trials, materials such as R-500 that are high in glucosinolates were immune to feeding pressures. This does not appear to be the case with feeding on the pods.

Both lodging and bird damage appear to induce more flowering in these varieties thus resulting in delayed harvest. This present problems in incorporating rape into a year round rotation system with cotton because it delays the harvest of the rape and results in planting dates for cotton that are too late.

Data from the past several years indicate that the best planting date for both rape and Crambe is in late October or early November. Delaying planting into December results in reduced yields due to high temperatures during flowering. For most varieties yields are stable when the crop is planted even in early October.

FUTURE PLANS: In 1999, the date of planting study of rape and crambe will be discontinued temporarily but evaluation of rape will be continued in a rotation study. Future experiments with growth regulators and fertility practices will be conducted in order to reduce lodging in susceptible varieties and improve varieties will be sought from Canadian breeding programs that concentrate on early maturing varieties of Canola. Irrigation and other agronomic studies will be conducted to make the yields of winter crops economical. Flowering data collected during the 1997-1998 crop year will be analyzed and an attempt made to determine the effects of lodging and other factors on flowering. Additional studies will be initiated to determine the water and fertilizer requirements of rape and crambe under local conditions. The results of the planting date by variety trial and water use and fertility trials will be used to develop a rotation system with cotton that will provide year round cover on the soil and should improve year round nitrogen management.

COOPERATORS: Dr. Paul Raymer, Coastal Plain Experiment Station, Tiffton, GA; Dr. Larry Sernek, Agrigenetics, Madison, WI; Dr. Jennifer Mitchell-Fetch, University of North Dakota, Fargo, ND; Dr. Duane Johnson, Colorado State University, Fort Collins, CO.

APPLICATION OF DRAIN-BACK LEVEL-BASIN SYSTEMS

D.J. Hunsaker, Agricultural Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer; and A. R. Dedrick, Supervisory Agricultural Engineer

PROBLEM: In the mid-1980s, in collaboration with a farmer, a novel level-basin irrigation system was developed in which a portion of the applied water is drained off the basin. The system is called “drain-back level basins.” Design, construction, management, and operational procedures were developed for their use in the mid-1980s by the U.S. Water Conservation Laboratory (USWCL). The drain-back level-basin (DBLB) system, unlike most surface irrigation systems, allows the application of small amounts of water per irrigation (less than two inches under some conditions), a highly desirable feature. The drain-back system features an earthen, water conveyance (inflow/outflow) ditch that provides both inflow to irrigate the basin (bench), and outflow to drain back some of the applied irrigation water. The ditch also serves as a surface drainage system to remove excess surface water from either over-irrigation or rainfall. Figure 1 illustrates the inflow/outflow ditch for a DBLB system consisting of four benches. Water is provided to all basins in the system from the supply canal. The lower frame of figure 1 shows the difference in elevation between the benches.

The drainage aspects of the system extend the area of application of level basins to high rainfall zones and builds on evaluations of level basins in high rainfall zones--graduate work done by Yvonne Reinink in the early 1980s. Since the system features earthen channels rather than concrete-lined ditches or closed-pipe water distribution systems commonly used with conventional level basins, the DBLB system is easier and less costly to construct than conventional level basins.

The farmer with whom we originally worked, Vess Quinlan in southern Colorado, developed significant acreage using the drain-back system. In 1983, we did an extensive on-farm evaluation of his system, finding that it worked very well. That experience led us to undertake further evaluation and documentation of the DBLB system, conducting field experiments to quantify the performance of the DBLB system and developing a data base for hydraulic model verification from carefully conducted field studies on precision-leveled furrows. These experiments resulted in a number of publications, both technical and popular, on the use of DBLBs.

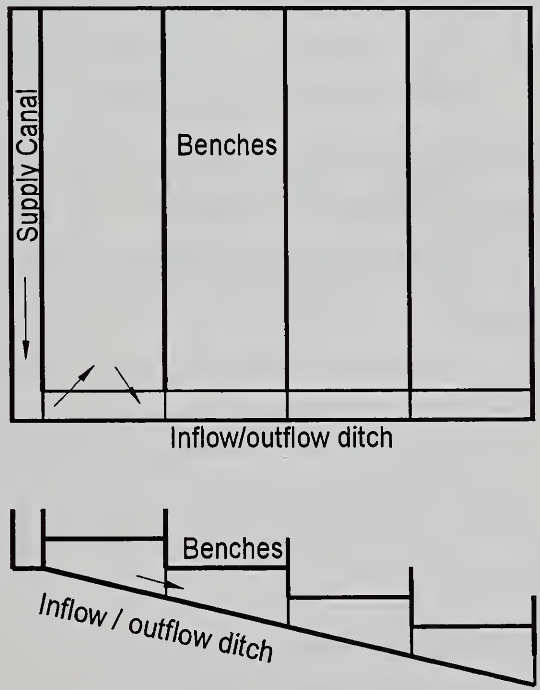


Figure 1. Schematic of a DBLB

DBLBs have been and continue to be installed on a several-hundred-acre farm in central Utah and are currently seeing rapid adoption in central Arizona, where several systems have been installed on farms since early 1997. The rapid adoption in Arizona has been initiated by Mr. Harold Payne, a private consultant to farmers in central Arizona, who is moving the idea/technology into practice. A description of the DBLB system, information on their installation and development costs, and an evaluation of their potential benefits to central Arizona were provided in last year's USWCL Annual Research Report (1997). To support further development and implementation of these systems, additional studies of DBLBs are needed to determine their current performance under central Arizona conditions and to obtain a database for comparison to hydraulic-model-generated performance parameters. Ultimately this information will be used to provide design guidelines for the systems and to determine their economic feasibility for conversion of existing sloping or poorly designed level basin systems. The objective of this research is to support the application of DBLB systems for water conservation and improved crop management.

APPROACH: Data on several DBLB systems installed in central Arizona are currently being collected and used for comparison to the irrigation model SRFR. In September 1998, an evaluation of drain-back level basin irrigation was conducted on an existing DBLB system designed for a silt loam soil. The system consisted of a series of seven benched level basins (each ≈640 by 660 ft) with a sloped, earthen, inflow/outflow ditch bordering the head of each basin. A concrete drop structure had been installed at the downstream end of the earthen channel in each basin except the last one in the series. Water flow through the 3.0-ft high by 6.0-ft wide structure opening was controlled with removable wooden boards placed in the opening. When the boards were removed, water from the basin drained through the opening in the drop structure and then through a 36-in closed-conduit corrugated pipe to the next basin.

The irrigation on September 3, 1998, was a mid-season irrigation for a grain sorghum crop that had been flat-planted to the fields in early July 1998. Data were collected during the irrigations for the first two basins in the system. These included measurements of infiltration using three, ring-infiltrometers within each of the two basins; advance and recession measurements at 24 stations set up in an 82.5-by-150-ft, length-by-width grid; measurements of water inflow rate to the system from the supply channel; and measurements of outflow rate from the basins using a Klaussen weir. The measured data for basin drain-back outflow, advance, recession, and water applied were compared to computed data from simulation.

FINDINGS: Water was applied to the first basin in the system at a flow rate of about 10.5 cfs. After 240 min (4 hr), the irrigator opened the drop structure of the basin and water drained off the field. It took about six hours to drain the excess water off. The outflow from the first basin marked the beginning of irrigation to the second basin. The depth of

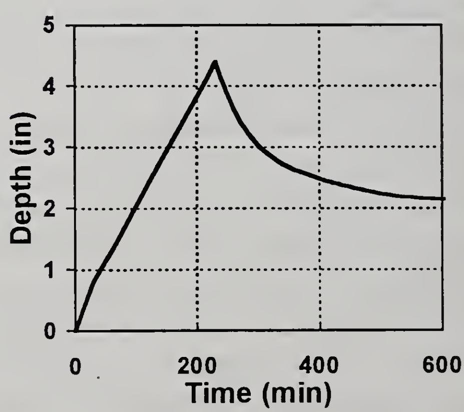


Figure 2. Water applied to Basin 1.

water applied with time for the first basin is shown in figure 2. A gross depth of 4.4 in of water had been applied to the basin after 240 min. A net depth of 2.2 in of water was applied after drain-back.

Figure 3 shows the flow rate computed with SRFR for the first basin and that actually measured. The volume of water that actually drained off the basin was larger than that predicted by the model. The difference between the two represented about 0.5 in of applied water.

The measured and predicted advance and recession curves for the first basin are shown in figure 4. The measured and computed advance closely match, whereas the computed recession occurred about 200 min longer than measured. Figure 5 shows the measured and predicted distributions of the depth of water applied with distance for the first basin. The model overestimates the measured depth of water applied by about 0.5 in. Figure 5 also shows that the uniformity of water applied was high for the first basin in the DBLB system.

The second basin in the system (data not shown) had a gross depth of application of 5.2 in and a net depth of 3.5 in.

INTERPRETATION: Based on these initial evaluations, the DBLB system in Eloy appears to be performing well. Under certain conditions, it may be possible to drain back as much as 50% of the water applied to a basin, although 25-33% drain back should probably be expected in most fields. The ability to apply light, uniform water applications with DBLBs is one of the most important features of the system.

The current modeling approach with SRFR is underpredicting surface drainage from these systems. The drain back flows create channels in the field, which could be contributing to more rapid drain back.

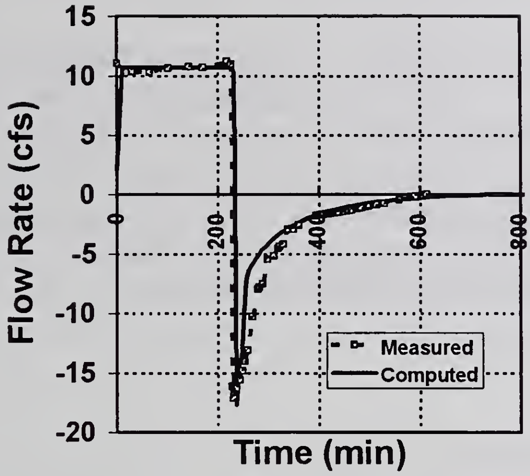


Figure 3. Flow rate for Basin 1.

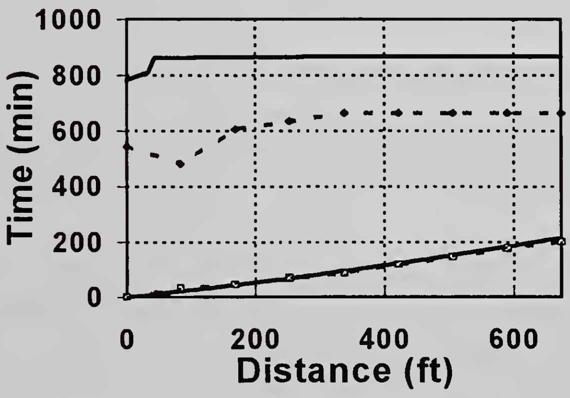


Figure 4. Advance and recession, Basin 1.

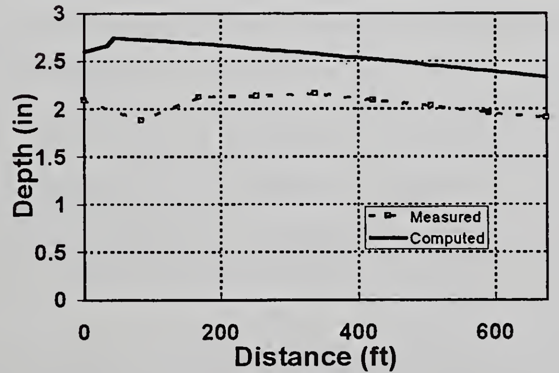


Figure 5. Water applied with distance, Basin 1.

Variations in elevations across the basin width also contribute to this prediction error.

FUTURE PLANS: The implementation of DBLBs will be monitored in other fields and soil conditions. Additional evaluation and data collection will advance modeling capabilities and development of more comprehensive design criteria.

COOPERATORS: Harold Payne, private consultant; Ed Martin, Irrigation Specialist; Jack Watson, Soil Specialist; and Tasmin Euseff, Graduate Student, The University of Arizona; and Chris Payne, consultant, Irrigation Management Service--Mobile Laboratories.

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and excessively, leading to wastage, soil loss, and pollution of surface and groundwaters. Computer solution of the governing equations with given irrigation conditions allows rapid evaluation of physical layout and operation. Systematic, repeated simulation can lead to design parameters yielding optimum uniformity of infiltrated water and minimum deep percolation and runoff from the end of the field. Inclusion of sediment and chemical transport in the models allows consideration of these aspects as well.

Most current models are limited to single furrows, or border strips and basins with zero cross-slope and a uniformly distributed inflow at the upstream end. But large basins are currently being irrigated from a single inlet. The flow spreads out in all possible directions, and any one-dimensional simulation of the distribution of infiltrated water must be viewed as a very coarse approximation. A non-planar basin surface can influence the flow as well. An irrigation stream concentrated in the lower-lying areas can significantly affect infiltration uniformity. Only a two-dimensional model can simulate these factors.

While a one-dimensional approach is suitable for furrows, in real fields, flows in neighboring furrows of a set are often coupled through common head and tail-water ditches. Tailwater from a fast furrow can enter a slower furrow from its tail end and modify its ultimate infiltration profile. To appreciate the effects of such coupling fully, simulation of interconnected furrows is necessary.

Irrigation management can influence the quality of both surface and ground waters as well as of the field soils. Irrigation streams can be of sufficient power and the soil structure lack sufficient resistance that soil boundaries erode, with the material entrained into the stream and transported downfield, reducing soil fertility upstream. Farther downstream, as infiltration reduces the discharge, or as the result of slope reduction, part of the load - perhaps only the coarse fractions- might deposit back onto the bed. Or else some or all of the entrained material can run off from the field, introducing turbidity into drainage water or depositing in quiescent areas, to the detriment of aquatic life.

Chemigation introduces agricultural chemicals into the irrigation water. Initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, chlorinated organic compounds, and heavy metals, for example, brought to farm fields in agricultural operations, and naturally occurring chemicals, e.g., selenium, can be transported to surface or subsurface water supplies by irrigation water, to the detriment of both human consumers of the water resource and wildlife dependent on the receiving water bodies. Pesticides attached to eroded soil particles in irrigation tailwater are an important example.

The objective of current development is to provide validated simulation models capable of providing quick responses to a wide variety of what-if situations, test combinations of design and management parameters. The models should be capable of simulating the transport and fate of sediment and chemicals, and thus capable of predicting the environmental response of a given agricultural field and its geologic site to

one or another irrigation-management practice.

APPROACH: Computer simulations would allow comparing various management modes in seeking an optimum. Recommendations could then be made on the basis of environmental considerations and water conservation and crop yield. Funding for this effort is provided in part by the Natural Resources Conservation Service.

For one-dimensional single-furrow, border strip, or basin simulation, user-friendly, menu-driven data input, output graphs, and text are linked to a simulation engine based on the universal laws of hydraulics applied implicitly in fully nonlinear form. Constants in commonly accepted empirical equations for infiltration and roughness are entered as input. The computer model, SRFR, is based on this approach.

Two-dimensional simulation is also based on hydraulic principles. Under the assumption of flow velocities small enough to neglect accelerations, force components in each of two mutually perpendicular directions on the field are in equilibrium. The resulting parabolic partial differential equations, solved implicitly by locally linearized finite differences in the two directions and time, yield a wave-like solution encompassing both wet and dry areas of the field. A similar but one-dimensional approach, treating wet and dry cells uniformly, is applied to multiple coupled furrows.

Erosion, transport, and deposition of irrigated soil is a complex matter, impossible to simulate on the basis of general physical principles alone. It is *fundamentally* an empirical science, in which the trend in recent years has been towards ever more general relationships, containing as much general physics as possible. Many conceptual models of parts of the total process have been proposed in order to avoid pure empiricism, but these are only partially convincing and are controversial, with researchers leaning toward one or another because of intuitive preference. The measure of a good predictive relationship or procedure is its generality with respect to different soils and different irrigation conditions, and ability to predict soil transport at different locations in a furrow, especially in the tailwater runoff, at all times during the irrigation.

FINDINGS: The SRFR 300-series user-friendly surface-irrigation simulation model has been formally released through the NRCS Water and Climate Center web site. A wide variety of surface-irrigation techniques and scenarios can be simulated with this menu-driven graphics-oriented program, including surge flow (featuring a variety of simulated commercial surge valves), level basins with drainback (see Fig. 1, for example), cablegation, cutback inflows, and the effects of badly graded fields or soils with varying infiltration characteristics along the length of run.

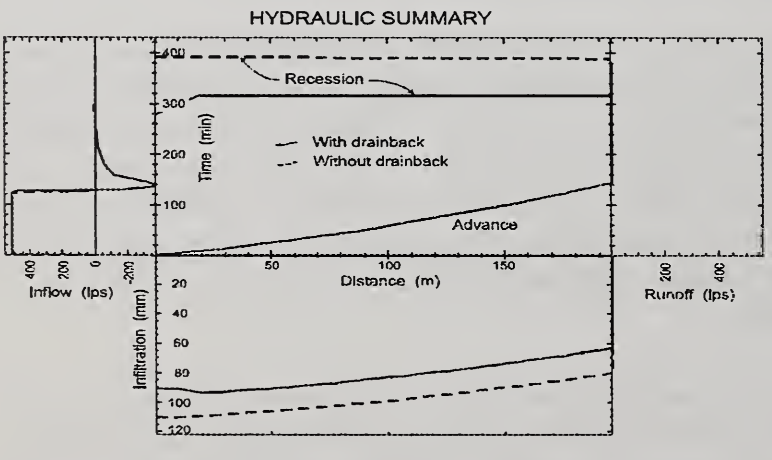


Figure 1. Comparison of level-basin management approaches.

A "first-cut" model, SRFR 400, computing erosion of soil characterized by a single representative aggregate size, has been constructed. The question is: will such a crude simulation reflect measured furrow sediment fluxes? Simulations with made-up data show qualitatively correct trends in transport across successive furrow sections, and in erosion and deposition within the furrows, at different flow rates

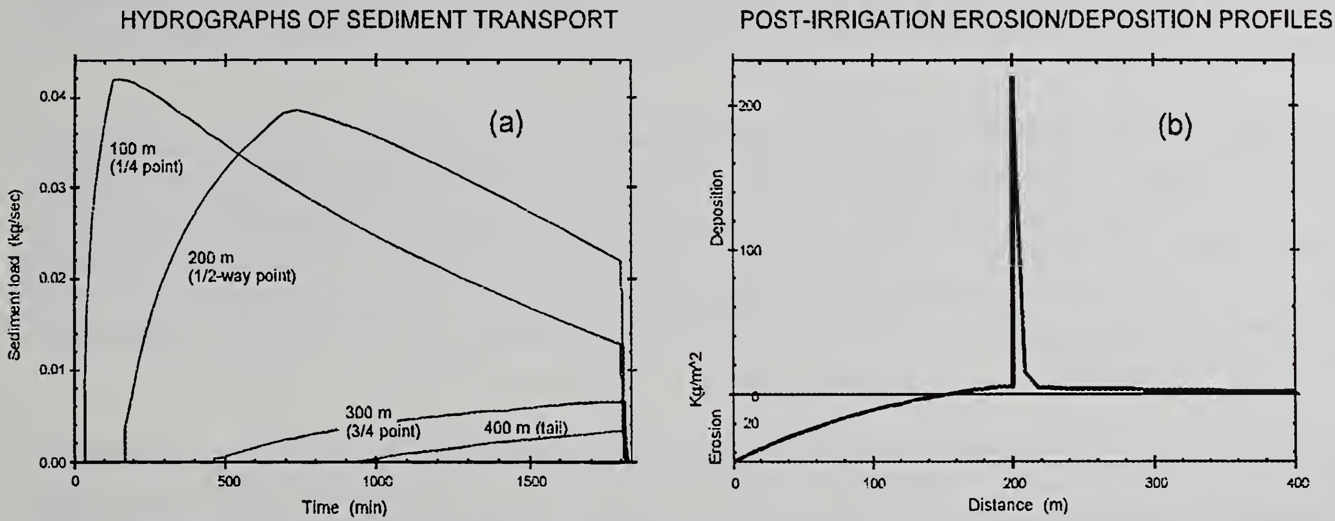


Figure 2. Broken slope: 1% followed by 1/2%. Yang transport-capacity formula. (a) sediment-load hydrographs; (b) post-irrigation erosion/deposition profiles.

and slopes, and with a broken slope (for example, steep followed by less steep -- see Figs. 2a, b). Bjorneberg's reduction of the Trout bean and corn experiments at Kimberly, Idaho, led to the first application with real data. In a test case it proved possible to reflect measured values of transport at the furrow quarter and end points, but only by postulating a representative sediment size well at the upper end of the sizes actually present in the mix.

A crucial component of erosion models is the formula for a flow's sediment-transport capacity. The half dozen or so standard formulas in use comprise more-or-less theoretically supported curve fits to flume and river data. The vast preponderance of data are in the sand and gravel range, up to and including cobbles. At the same time, the heavily empirical orientation of the research precludes much extrapolation beyond the range of soils comprising the test data. The Laursen (1958) formula was selected by cooperating Spanish scientists because of the inclusion of silts in Laursen's test data. This was the formula used in SRFR 400 as well. In application to the Trout data, the transport capacity and the erosion based on a representative aggregate size in the mid range of measured sizes proved greatly over-predicted, and deposition in the lower furrow sections under-predicted. The Yalin (1963) formula used in WEPP provided substantially worse predictions. The Yang formula (1973), on the other hand, qualitatively reproduced the measured values, with a representative sediment size much closer to the mid-range of the measured mix.

The current model has as output: sediment-transport hydrographs at user-selected points along the furrow (kilograms per second and in concentrations by weight and volume); post-irrigation cumulative erosion and deposition depth profiles (local kg/m^2), separately and in combination; and soil-loss figures (tons/hectare) from the successive reaches of the furrow. For experimentation, the transport-capacity formula can be selected, as can several other simulation assumptions.

INTERPRETATION: The growing body of simulation software is finding users in the national and international irrigation community for design, management, and evaluation of surface irrigation. It is likely that studies of the interrelationship among distribution uniformity, standard deviation of surface elevations, and inflow rate will provide a useful adjunct to current design software. Absolute predictions of soil erosion, transport, and deposition appear to be significantly less accurate than predictions of hydraulic performance, but the influence of design and management is easily discerned, so that these aspects can also be taken into account

FUTURE PLANS: Deficiencies in SRFR noted by users will be addressed, including coalescing of successive surges. As funding becomes available, the pilot two-dimensional model will be reoriented towards routine application; numerical solution parameters will be adjusted automatically in response to solution behavior. Methods for increasing the allowable time step, currently very small in basins with fine definition of soil and water surfaces, will be explored. The coupled multiple-furrow model will be completed, and additional field verification for both the two-dimensional and the multiple coupled furrow programs will be sought.

In the short term, additional simulation/field-measurement comparisons of Trout bean and corn runs and Bjorneberg and Lentz runs of 1998 will be made. The sensitivity of the transport results to the various components of the input data will be studied. The erosion calculations will be made truly unsteady, rather than a sequence of steady states as in both WEPP and the Fernandez model (IAS, Spain).

In the longer range, various ways of incorporating actual sediment-size distributions into the model will be considered, better to match observations. WEPP includes partial consideration; Fernandez formally tracks eight sizes, but in accord with but one speculative view of particle-arrangement geometry in the soil matrix.

Long-term plans include incorporation of relationships for cohesive soils. This is a far less traveled area in the field of sediment transport than non-cohesive soils. Incorporation of soil-chemistry components is contemplated: water and soil salinities play a great role in erosion, especially in clay soils. Estimation should be made of the pre-wetting effect for surge irrigation. Soil and water temperature effects on infiltration and erosion phenomena should be quantified.

As funding becomes available, chemical transport and fate will be included in SRFR.

COOPERATORS: Thomas Spofford, Natural Resources Conservation Service, National Water and Climate Center, Portland, OR; Luciano Mateos, Rafael Fernandez, Instituto de Agricultura Sostenible, CSIC, Cordoba, Spain; David Bjorneberg, Rick Lentz, Robert Sojka, ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho; Thomas Trout, Water Management Research Laboratory, Fresno, CA; D.D. Fangmeier, University of Arizona; Marshall English, Oregon State University; Roger Stone, Gila River Farms, Pinal County, AZ.

WATER PROJECT MANAGEMENT

CONTENTS

WATER PROJECT MANAGEMENT

MISSION

To develop tools for the management and augmentation of water supplies in arid-region water projects, particularly those associated with irrigation. This includes methodologies for measuring and monitoring water fluxes with natural and man-made systems, methods for improving control of water within distribution networks, conjunctive management of groundwater and surface water supplies, artificial recharge of groundwater, natural water treatment systems (e.g. soil-aquifer treatment), and methods for assesing the performance of water projects in terms of water quality and quantity management.

IRRIGATION FLOW MEASUREMENT STUDIES IN CLOSED PIPE SYSTEMS

J.A. Replogle, Research Hydraulic Engineer and B.T. Wahlin, Civil Engineer

PROBLEM: Several problems concerning pipeline flows serving irrigated agriculture are of continuing concern. These include flow profile conditioning in pipes, field applications of several flow meters used with irrigation wells, and the effects of flap gates on pipe outlets. Several pipe flow metering devices are limited in their field use on discharges from wells. Propeller meters, end-cap orifices, and Pitot systems are among these. All of these are affected by upstream pipe bends and valves. Propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. End-cap orifice meters do not work well on rusted pipe ends. Pitot systems are considered difficult to apply to discharges from wells without special wall taps and insertion ports. Inserting a standard combination Pitot-static tube such as the Prandtl tube into the outflow end of a pipe has been used. However, these tubes are expensive, requiring specialized manufacturing techniques not available in most machine shops. Flap gates at the end of pipes exert a back pressure into the upstream piping. Whether this back pressure is significant to some applications is questioned by users. The back pressure due to the gate weight and the stiffness of the flexible hinges is not well established. Problems with determining the accuracies of meters for municipal water supply withdrawals from the Great Lakes by Chicago-area cities are being studied in support of the US Geological Survey (USGS) and the US Army Corps of Engineers (COE).

The ongoing objective associated with pipe system flows is to improve the accuracy, reliability and efficiency of control devices. More specific objectives include: (a) verify the design and calibration of a modified Pitot system for irrigation wells that can be constructed in ordinary shop settings; (b) complete the technical notes on the end-cap orifice; (c) quantify the back-pressure effects of flap gates at pipe outlets; (d) continue to develop practical methods to achieve effective flow conditioning in pipe outlets; (e) evaluate prototypes of clog-resistant propeller meters that have been manufactured to our specifications; and (f) support USGS and COE in evaluation the accuracy of withdrawals from the Great Lakes by Chicago and neighboring cities.

APPROACH: (a) A portable Pitot-tube system was designed and constructed for evaluation in a laboratory setting, with field trials on actual irrigation wells. The evaluation is intended to establish (1) the probe sampling distance up the pipe, (2) that the Pitot traverse can be vertical, horizontal, or other, (3) how many point readings are required for useable accuracy, and (4) where these point readings should be located. Special features sought include an effective, economical system that can be easily constructed; rugged enough to withstand likely field conditions; provide a way to obtain the static pressure for a Pitot-static tube system without tapping the pipe wall; handle the effect of pipe roughness due to corrosion, rusting, etc.; and accommodate partly full pipes.

(b) Standard calibration procedures were previously completed on the end-cap orifice system using the laboratory weigh tank. An alternate pressure tapping system for the end-cap orifice uses a small static pressure tube (with holes drilled through its walls), similar to that used for the Pitot system described above, to detect the pressure in the large pipe upstream from the orifice. The tube was

inserted through a grommet-sealed hole in the face of the orifice plate near the pipe wall so that the pressure sensing holes would be one pipe diameter upstream from the face of the orifice.

(c) The flap gate study included observing the pressure grade line changes with and without the flap gate in place, and with various weights added to the flap gate.

(d) Methods to condition flow profiles in pipe outlets will include insertion of minimum contraction orifices and sidewall vanes. A special 30-inch diameter pipe facility has been constructed to conduct tests on flow conditioning. A proposed conditioner was installed on an 8-in laboratory pipe for use in the Pitot study.

(e) A meter builder in Fair Oaks, California, (Global Water), constructed and furnished two industrial propeller meter prototypes following our debris shedding design proposals. They will be tested in the 30-inch diameter pipe facility mentioned above. An ultrasonic velocity probe will be used to define the flow field.

(f) The study of the Chicago area water withdrawals is being modeled after the processes used in the Imperial Irrigation District, CA, that was reported last year. Statistical studies of records and of meter performance data are the main source of inputs.

FINDINGS: (a) Referring to Fig. 1, the Pitot-static system consists of an impact pressure sensing tube (a), the static pressure sensing tube (b) with pressure sensing holes (c), a folding manometer board with flexible tubing attached (d), an optional scale marked in velocity units (e), rubber end dams and C-clamps (f) that can be used to produce sufficient back pressure to maintain full pipe flow at the measurement plane, a mounting bracket frame (g), vertical positioning clamp screws (h), plugged tube extensions (i) that can be used to align the probes visually, a securing strap or chain (j), and a handle for alignment and vertical reference (k).

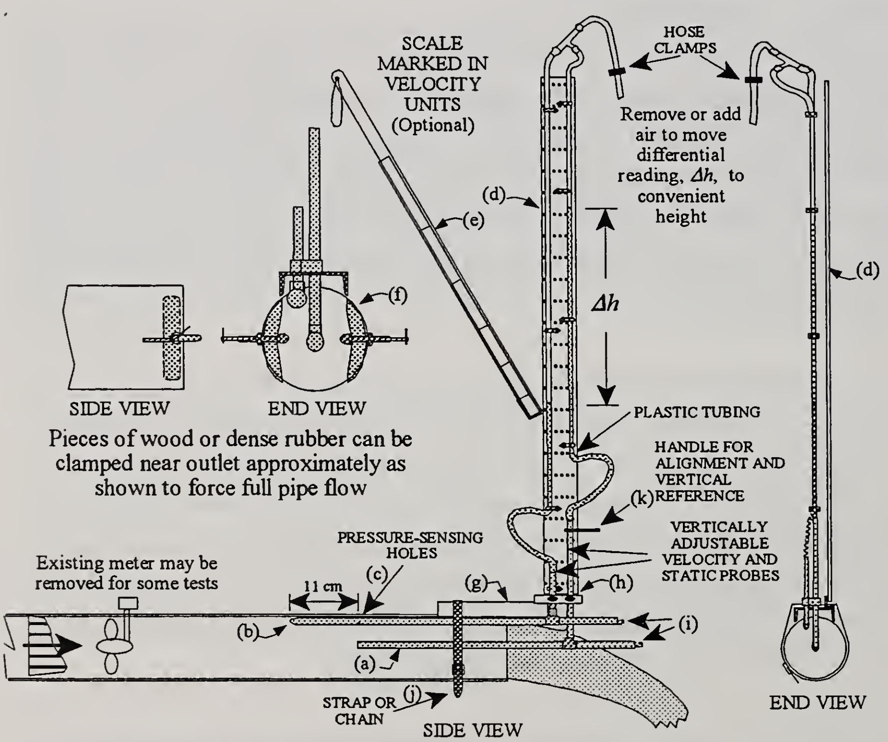


Figure 1: Pitot system shown as it might be used to evaluate a propeller meter installation

The portable measuring system developed can measure the flow rate of wells that discharge into irrigation canals or streams. The rugged compact system is convenient enough for field use and can be fitted into a standard business briefcase. Four points at prescribed locations can define the average flow velocity similar to a ten-point traverse, (± 3 %) but without velocity profile information. Even two points properly located can provide average velocities within ± 5 %. Important findings include: (1) Static pressure can be obtained without drilling holes in the well pipe, and (2) The pipe roughness affects the "bullet" shape of the velocity profile, regardless of the distortion from system plumbing (Fig. 2), but the average velocity and the effects of both roughness and distortion can be suitably measured by two-, four-, or ten-point traverses. For the ten-point traverses, the pipe circle is divided into five concentric equal areas. For the four-point method, two concentric but equal areas are used (Fig. 3). For the two-point method, the same point locations are used as for the four-point method, except only one point on each ring is used and these points are on opposite sides of the flow region. Partly full pipes can be accommodated by clamping obstruction blocks on the end partly to block the outlet and cause full pipe flow (Fig 1,f).

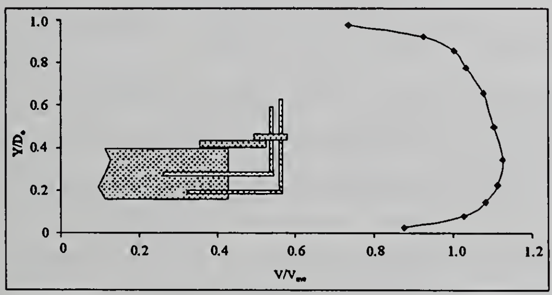


Figure 2. Velocity distribution. The distortion of the profile is typical.

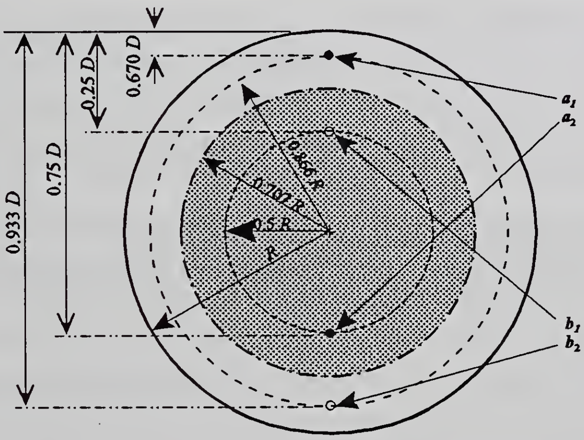


Figure 3. Points a_1, a_2 or b_1, b_2 are used for two-point method, both for four-point method.

(b) End-cap Orifice: The orifice system (Fig. 4) calibrated as expected from theory, and is more repeatable than corner tappings on a pipe of uncertain end quality. The convenience aspects of the system were demonstrated.

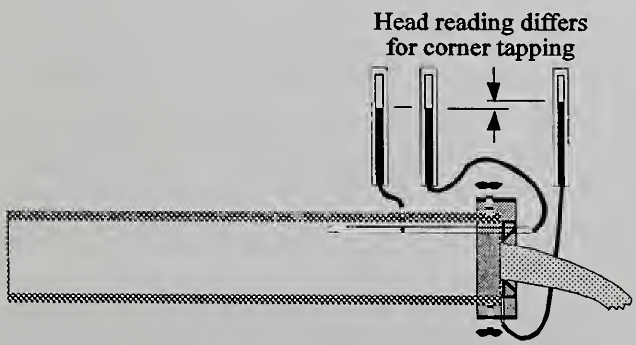


Figure 4: Static pressure probe and wall pressure tap produce similar results, but both differ from flange-tap calibrations.

(c) Flap Gate: We expected that as the flow in the pipe increased, the change in the pressure grade line should decrease because there would be more kinetic energy used to keep the flap gate open. However, no distinct pattern could be seen from the data. Low flows and high flows produce back pressures on the order of only 4 mm to 6 mm of water column.

(d) Flow Profile Conditioning: Not completed. However, a preliminary trial was installed in an 8-inch pipe with two elbows not in the same plane, which was the pipe system used in the Pitot experiment. This configuration causes strong distortion of the flow profile and strong spiral flows.

(e) Propeller Meter: Not completed.

(f) For the City of Evanston, the accuracies of the individual flow measurements and annual volumes are within ± 2%. Similar results are expected for pumping stations within the City of Chicago.

INTERPRETATION: (a) Pitot System: An economical and portable system that is easily constructed is now available to measure flows from irrigation wells. It can be used when the approach pipes are too short for orifice meters or propeller meters and the profile is distorted. It can also be used on flows from partly full pipes by causing the pipe to flow full with stiff rubber strips C-clamped on either side of the pipe outlet. (b) End-cap Orifice: This version of the end-cap orifice can be installed on well pipe outfalls without any specially drilled holes. The corner tap locations of the original version, which also did not require pipe drilling, are somewhat sensitive to poor pipe end conditions. While this version cannot be used if the pipe is in badly eroded condition, it is somewhat forgiving. The orifice still requires the installation to provide standard lengths of straight pipe from the last pipe bend. While it may appear to be a somewhat less desirable option that the Pitot system, it is more readily left in place unattended than the Pitot system, which usually must be traversed across the pipe for most applications. (c) Flap Gate: While the analysis is incomplete, preliminary findings are that flap gates cause negligible back pressure on pipelines that are flowing full. The difference between low and high speed flow was not significant. (d) The attempt to condition the flow through two elbows not in the same plane produces fairly good results with only slight distortion of the velocity profile (Fig. 2). (f) Statistical studies of well-kept records of water delivery operations can identify problems in metering accuracies and provide assurances of performance goals.

FUTURE PLANS: (a) Pitot System: Two technical papers are under review. One presents the laboratory and field study results. The other describes the construction and application techniques. These will be followed through to publication. (b) End-cap Orifice: report is being prepared. (c) Flap Gate: More evaluation to try to obtain a better description of hydraulic behavior is planned. (d) Flow Profile Conditioning: Start laboratory study phase and refine test facility. (e) Conduct this study in conjunction with the flow profile study. (f) Complete study and finish report to USGS and COE.

COOPERATORS: Maricopa Agricultural Center, Univ. of Arizona (Robert Roth), Buckeye Irrigation District (Jackie Mack), Wellton Mohawk Irrigation and Drainage District (Charles Slocum), Global Water (John Dickerman), Plasti-Fab, Inc. (John Vitas),and USGS/COE (Kevin Oberg/David Kiel).

FLOW MEASUREMENT AND CONTROL IN OPEN CHANNEL IRRIGATION SYSTEMS

J.A. Replogle, Research Hydraulic Engineer; B.T. Wahlin, Civil Engineer; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEMS: The following continuing problems concerning open channel flow measurement and control are being addressed.

(a) Discharge measurements in sediment-laden flows in natural streams are difficult because of sediment accumulations.

(b) Unstable deliveries from a main canal to a secondary canal increase the difficulty of effective irrigation and may require expensive means to monitor total delivery volume.

(c) Parshall flumes have been popular flow measurement devices for open channels since their introduction in 1926. Traditionally, problems have arisen in Parshall flumes if they are not constructed to specifications. For example, a large Parshall flume installed in California has a field-verified calibration that differs by 10% to 20% from the historical calibrations for that size.

(d) One of the most important factors in installing a broad-crested weir is vertical placement of the sill. If the sill is too low, the flume may exceed its limit of submergence. If the sill is too high, upstream canal banks may be breached.

(e) The FLUME3 program does not run well with Windows 95.

APPROACH: The general objective is to address these problems economically and practically with user-friendly technology.

(a) A prototype self-calibrating flume for sediment-laden flows was designed and installed in northern California (Fig.1). The objective is to evaluate the idea of the self-calibrating flume system and to determine its operational limitations. The design was based on estimated hydraulic behavior of a chute outlet attached to a "computable" trapezoidal long-throated flume. Two stilling wells, one on the main flume and one on the chute, are expected to provide field calibration for the chute after the main flume no longer can function because of sediment deposits. A laboratory model is part of a thesis study at the University of Arizona to check the limits of sediment handling, the best slope for the chute, and whether the calibration of the chute remains stable after the sediment fills the main flume.

(b) A new float-operated valve that can be used in combination with a water inflated bag is proposed to be inserted into the pipeline from a main canal to a secondary canal to maintain a desired flow level at locations without electric power. The objective is to develop hydraulic flow control devices applicable where electricity may not be available. This is an extension of the previously developed DACL (Dual Acting Controlled Leak) systems.

(c) The historical calibrations of a one-fourth scale model of an eight-foot Parshall flume were previously verified. The objective is to develop methods to modify wrongly constructed Parshall

flumes to recover their function for accurate flow measurement and to identify construction anomalies that can cause large calibration shifts . The same model will be fitted with a modified entrance and other changes in an attempt to identify causes of calibration shifts that have been noted in a larger Parshall flume.

(d) Compilation of field experiences by users of the commercialized version of the patented adjustable-sill, long-throated flume will be used to advise on expansion of the product line, and to evaluate field durability and vulnerability to damage from frost and animals. The objective is to evaluate field installations and to assist in design and materials changes that may be needed to hasten technology transfer.

(e) New software will be written to make flume calibration and design software compatible with the computer Windows environment.

FINDINGS: (a) The field installation of the self-calibrating flume (Fig.1) was destroyed by flash flooding that greatly exceeded the design flume capacity. It was salvaged, rebuilt and reinstalled in January 1998. Some subsequent discharge events were successfully measured.

The California Water Quality Control Board used the flume data from last year to demonstrate the severity of the cinibar tailings (mercury ore) problem to EPA. Using the discharge calculations from the flume, a turbidity meter, and field-calibration data, 77 kilograms (170 lb) of mercury was calculated to have left the site in January and February 1998. Based on that, emergency super-fund cleanup ($2.5 million) to stabilize the mine tailings were authorized.

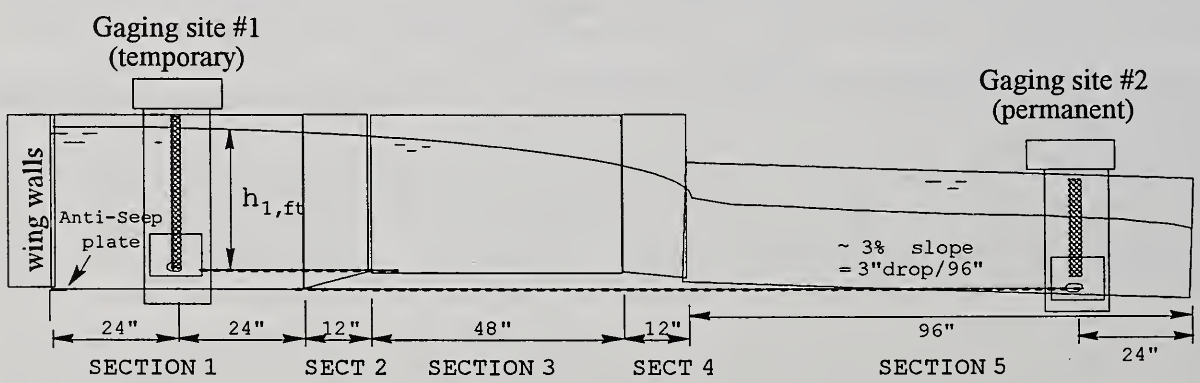


Figure 1. General layout of sediment resistant flume as installed.

The laboratory model study is progressing well and is expected to be completed by January 1999. Some summary results are shown in Fig. 2. Basically, the sediment (sand) altered the upstream (subcritical) stilling well as predicted. The downstream stilling well in the chute (supercritical) has about the same response with and without sand, as postulated. The most reliable point of sampling the chute appears to be near the center of the chute rather than at the downstream quarter point, as used in the field prototype.

(b) Further development of a new DACL valving system was considered after a commercial version did not provide the needed functions. The new valve appears to be capable of all required functions

but needs to be laboratory and field proven. A variety of low-cost bag products has been collected. None have been tested yet.

(c) A 50-foot Parshall flume, whose calibration differs from published calibrations by 10% to 20%, was constructed with a modified entrance flare that differs from the published rounded entrance. This modification is suspected of causing the calibration difference. Laboratory model studies to verify this are incomplete.

(d) Field observations and reports have been compiled for flumes ranging in size from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). The users find the devices easy to install and able to meet their operating requirements. The standard versions are now commercially available under the name "Adjust-a-Flume" (Nu-Way Flume and Equipment Company). Widespread acceptance appears to be growing, as is interest to adding recording instrumentation to the product line that is complicated by the movable reference throat level.

(e) The WinFlume program has been distributed in trial versions to many users.

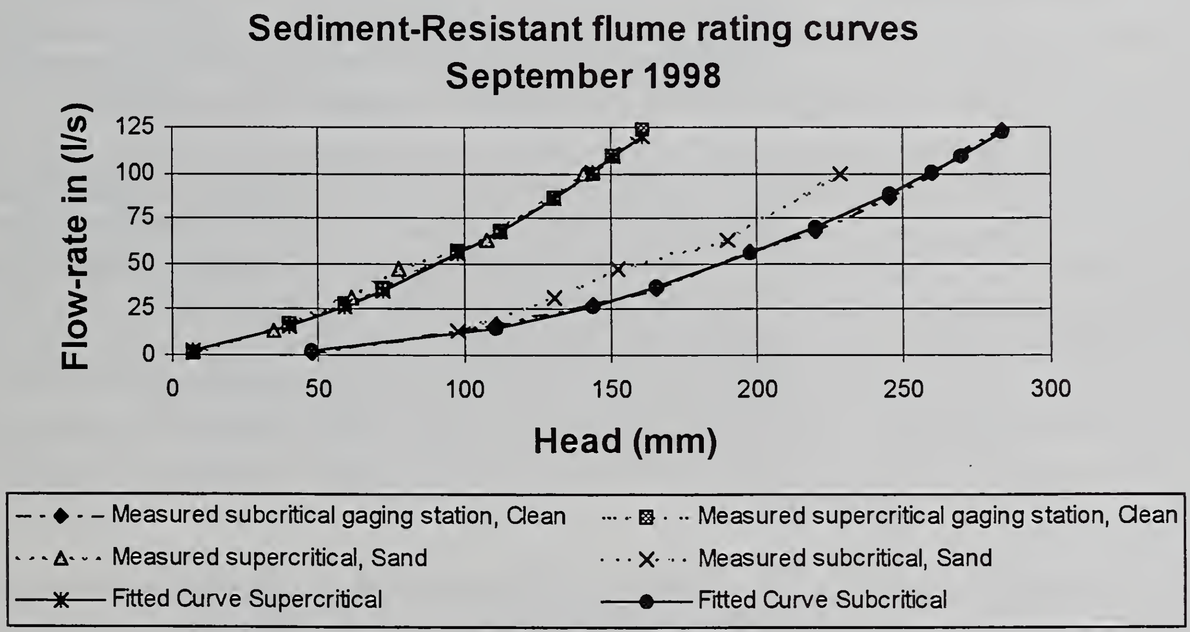


Figure 2. Results of clear water and sand bed load on 3% sloping chute outlet for two stilling wells, one at the usual upstream subcritical region of a long-throated flume and one at the midpoint of the chute or super-critical region.

INTERPRETATIONS: (a) The ability to measure flows in heavy sediment carrying flows is important to studies of erosion and runoff and the effectiveness of best management practices on watersheds. The system, if successful, expands the range and flume shapes available for such use.

(b) Stable flows in secondary canals permits low-cost totalization of flow deliveries to farms because time clocks will suffice instead of complex recorder systems. Stable, constant flows allow more precise management of irrigation systems.

(c) Parshall flumes may not behave as originally specified if installation differs from the standard. While some liberties with the constructed shapes are possible, these need to be clearly identified. One of the most important seems to be the entrance that is frequently modified from the specified rounded shape. Often converging walls are substituted.

(d) The field problems involving the vertical placement of flumes and broad-crested weirs are greatly reduced for farm-sized earthen channels by the commercialization of a series of semi-portable, long-throated flumes with adjustable throat sills and capacities ranging from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). Sizes above 6 cfs are not intended to be portable.

(e) The new flume program will hasten the technology transfer of good flow measuring and monitoring for irrigation management.

FUTURE PLANS: (a) The sediment resistant flume in California will continue to collect data from storm events.. The laboratory model study will be completed. A second, clear-plastic model is being considered so that sediment movements can be observed more readily.

(b) The new DACL valve will be laboratory and field evaluated for desired control functions. Further laboratory and field evaluations for function and durability of assembled control systems using the concepts will be reinitiated.

(c) A 4:1 scaled-down model of an eight-foot Parshall flume will be calibrated, modified, and evaluated. Length-to-depth relationships in flumes are to be investigated. The findings for the field installation of the 50-foot Parshall flume will be evaluated on this model by modifying the entrance to see if a calibration shift can be produced, even though the 8-foot Parshall flume is not a scale model of the 50-ft version, the latter being much shorter in length compared to its width (Fig. 3).

(d) Advice on design changes for adjustable flumes and evaluation of field performance will continue.

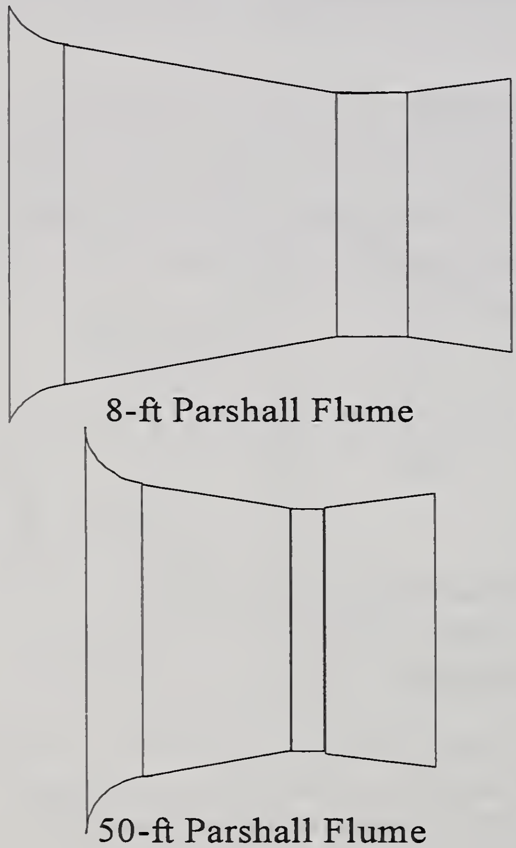


Figure 3. Relative proportions of 8-ft and 50-ft Parshall flumes.

COOPERATORS: Informal cooperation exists among: US Bureau of Reclamation (Tony Wahl, Cliff Pugh, Hydraulics Laboratory, Denver); Natural Resources Conservation Service (Harold Bloom); Imperial Irrigation District (Anisa Divine); Salt River Project (Joe Kissel, Kirk Kennedy); Wellton Mohawk Irrigation and Drainage District (Charles Slokum); Maricopa-Stanfield Irrigation and Drainage District (Brian Betcher); Buckeye Irrigation District (Jackie Mack); Plasti-Fab, Inc.(Randy Stewart); University of Arizona (Don Slack); California Water Quality Control Board (Dyan White); and Nu-way Flume and Equipment Company (Charles Overbay).

WATER REUSE AND GROUNDWATER RECHARGE

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Increasing populations and finite water resources necessitate more water reuse, as do increasingly stringent treatment requirements for discharge of sewage effluent into surface water. The aim of this research is to develop technology for optimum water reuse and the role that soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. Present focus in the U.S. is on sustainability of soil-aquifer treatment, particularly the long-term fate of synthetic organic compounds (including pharmaceutically active chemicals and disinfection byproducts) in the underground environment. The fate of pathogens and nitrogen also needs to be better understood. In Third World countries, simple, low-tech methods must be used. Such methods will be applied to demonstration projects in the Middle East and North Africa under the White House Middle East Peace Initiative, the Technology for International Environmental Solutions (TIES) program of USDA and EPA, and the Middle East Regional Cooperation Program (MERC) of the U.S. Agency for International Development (USAID) in cooperation with the National Research Council (NRC).

Artificial recharge with infiltration basins for storing fresh water underground as part of integrated water management or conjunctive use of surface water and groundwater, or for underground storage and soil-aquifer treatment (SAT) of sewage effluent for water reuse, is still rapidly increasing. The permeable soils that such systems require are not always available, so that less permeable soils like the loamy sands, sandy loams, and even light loams of agricultural and desert areas are increasingly used to obtain recharge and SAT benefits. Such soils require reliable techniques for infiltration measurements and other pre-investigations to assess the feasibility of the project, and for management of recharge basins to maintain maximum infiltration rates. Climate change is going to be an important factor in future management of water supplies. Because it is impossible to predict it with any accuracy on a local or regional scale, managers increasingly must develop flexible water management schemes so that they can handle excessive as well as inadequate water supplies. This requires more long-term (years to decades) storage of water or "water banking," which is best achieved via artificial recharge of groundwater to avoid the evaporation losses that occur with long-term surface storage behind dams.

Long-term effects of irrigation with sewage effluent on soil and underlying groundwater must be better understood so that future problems of soil and groundwater contamination can be avoided. Potential problems include accumulation of phosphate and metals in the soil and of salts, nitrate, toxic refractory organic compounds, and pathogenic micro-organisms in the groundwater. Water reuse is a good practice, but it should not ruin the groundwater. Long-term salt build-up in groundwater will also occur in groundwater below any irrigated area (agricultural or urban), regardless of the source water, if there is no drainage, groundwater pumping, or other removal and export of salt from the underground environment. Groundwater levels then also will rise, which eventually requires drainage or groundwater pumping to avoid waterlogging of surface soils and formation of salt flats. In urban areas, such groundwater rises will damage buildings, pipelines, landfills, cemeteries, parks, landscaping, etc. The salty water removed from the underground environment must be properly

managed to avoid problems. Stream depletion by groundwater pumping and solving conflicts between users of surface water and groundwater continue to be a challenge in many parts of the world. Research objectives include chemical analyses of groundwater samples from below areas with a long history of irrigation to see what is there, and conducting sewage-irrigated column studies for a detailed analysis of transport and fate of contaminants in the upper underground environment.

APPROACH: Technology based on previous research at the USWCL and more recent research are applied to new and existing groundwater recharge and water reuse projects here and abroad. Main purposes of the reuse projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes. A Southwest regional project has been developed to get more information about fate of synthetic organic compounds, nitrogen, and pathogens in the underground environment so that projects can be designed and managed (including optimum pretreatment) to achieve desirable results, especially for potable use of the water from the aquifer. The project has been set up for about four years and involves six existing field systems in Arizona and California, four universities, and numerous water districts, municipalities, and other participants and sponsors. Long-term effects of sewage irrigation on soil and groundwater will be studied in a cooperative project with Arizona State University and the U.S. Army Garrison at Fort Huachuca, AZ, using the Fort's golf course that has been irrigated with Army sewage effluent for about 30 years. Laboratory studies will also be performed, using 8 ft soil columns and various irrigation efficiencies, including a low efficiency to simulate replenishment irrigation. An experimental recharge facility will be installed by the City of Surprise with financial support from the Arizona Department of Water Resources to develop optimum management principles for recharge basins in fine-textured soils. Various scenarios of rising groundwater levels and salt buildups due to irrigation were analyzed and compared with field data to get an idea of rates of rise in groundwater levels and salt contents of the upper groundwater, and how to handle this water (disposal in salt lakes, sequential irrigation of increasingly salt tolerant crops ending with halophytes to concentrate the salts in smaller volumes of water, membrane filtration to remove the salts and allow municipal or agricultural use of the water, and disposal of the reject brines).

The validity of legal concepts to resolve conflicts between uses of surface water and groundwater has been tested against the real effects of groundwater pumping on streamflow obtained by analyses of underground flow systems for different conditions of hydrogeology.

FINDINGS: Field and laboratory tests continue to show the usefulness of recharge and soil-aquifer treatment in water reuse. Main issues still are sustainability of soil-aquifer treatment and fate of recalcitrant organic compounds, including disinfection byproducts, pharmaceutically active chemicals, and humic and fulvic acids and other organic compounds that react with chlorine to create new disinfection byproducts. Analysis of the water and chemical balance (including salts) indicates that the drainage or deep-percolation water from sewage irrigated fields will be seriously polluted, especially in dry climates. Because of the resulting groundwater pollution, well pumps will be shut down and groundwater levels will rise about 1m per year as predicted by simple calculation. Eventually, groundwater pumping must be resumed to keep water tables at safe levels. Management

alternatives to minimize environmental damage from this water have been developed.

INTERPRETATION: The developments of better technologies or concepts for predicting infiltration rates with cylinder infiltrometers, estimating volumes of water that can be stored underground for water banking, and managing relatively fine textured soils to achieve maximum infiltration for recharge will extend the use of artificial recharge of groundwater to "challenging" soil and aquifer conditions. This will enable water resources planners and managers to benefit from the advantages that artificial recharge offers in conjunctive use of surface water and groundwater, in water reuse, and in integrated water management. The development of basic relations between groundwater pumping and depletion of streamflow will enable the legal profession to develop rules and regulations for conjunctive use of surface water and groundwater that are based on sound hydrologic principles.

FUTURE PLANS: These plans primarily consist of continuing existing research and of developing new research projects, mostly with universities and water districts, on long-term effects of irrigation with sewage effluent on soil and groundwater (field and laboratory studies), salt and ground water management in inland areas with water and salt imports but no exports, control of bio-clogging of recharge wells or trenches by super disinfection of water entering the well and creating a permeable biofilm or bioreactor zone at some distance from the well, and management of clogging layers in infiltration basins to obtain treatment benefits from the clogging layers while avoiding drastic reductions in infiltration rates. Infiltration test plots will be installed to verify concepts of recharge basin management developed for finer textured soils where clogging, crusting, fine particle movement or wash-out wash-in, hard setting, and erosion and deposition can seriously reduce infiltration rates. Specific plans include a soil-column study in a USWCL greenhouse in cooperation with ASU to determine inflows and outflows of chemicals for various crops (grass, alfalfa, bare soils) and irrigation efficiencies (low, medium, high) using chlorinated tertiary effluent from the 23rd Avenue Phoenix sewage treatment plant. The field testing facility at the City of Surprise will consist of about 10 recharge basins of about 20x100 ft each and will use tertiary effluent from the Surprise South Wastewater Treatment Plant. Different management schemes (flooding and drying cycles, surface conditions, tillage and cleaning operations, rolling, dragging, chemical additions, etc.) will be tested to see how recharge systems in fine soils like sandy loams to light loams should be managed to minimize clogging, crusting, wash-out wash-in, hardsetting, and other processes that reduce infiltration to achieve maximum infiltration for "challenging" soils. In addition, there will be the usual technology transfer and professional society activities.

COOPERATORS: Dr. P. Fox, Dr. P. Westerhoff, Dr. J. Drewes, Arizona State University; Dr. R. Arnold, Dr. M. Conklin, University of Arizona; J. Swanson, The City of Surprise; and Fort Huachuca, Arizona, United States Army Garrison through ASU and M. Milczarec of GeoSystems Inc., Tucson.

MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR NATURAL RESOURCES

E. Bautista, Agricultural Engineer; A. R. Dedrick, Supervisory Agricultural Engineer; and S. A. Rish, Program Analyst

PROBLEM: Enhanced long-term management of water and other natural resources, grower profitability, and overall social well-being are essential to a sustainable irrigated agriculture. Because approaches to these objectives are often uncoordinated, all agricultural stakeholders--farmers, irrigation districts, other support and regulatory organizations, and other interested parties--need to interact proactively to address these needs. To this end, the Management Improvement Program (MIP), a management process similar to those used to improve the performance of corporate organizations, was applied to the business of irrigated agriculture (Figure 1). The purposes of this research were (1) to develop and apply the MIP methodology in an agricultural area, and (2) to refine the methodology for future use. Expected outcomes of the MIP application were the establishment of a framework for managed changed in the demonstration area, with the participation of relevant agricultural system stakeholders, and changes in on- and off-farm management practices consistent with the goal of improving the sustainability of the agricultural system.

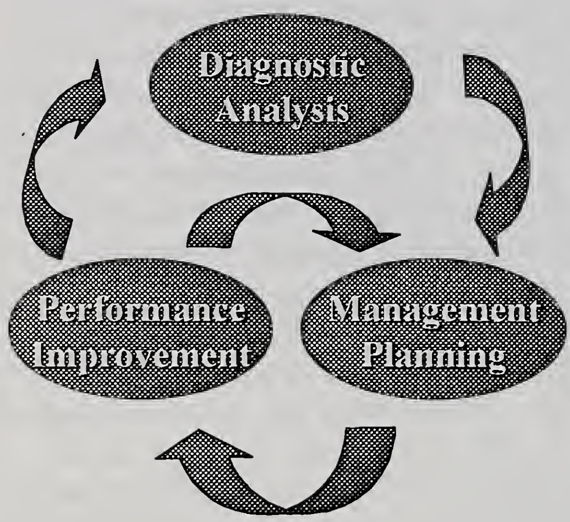


Figure 1. The three phases of the Management Improvement Program. Diagnostic analysis yields an interdisciplinary understanding of the performance of irrigated agriculture in the area. Management Planning results in a shared understanding of the performance among stakeholders, joint identification of opportunities for improvement, and planned managerial and technological changes to address those opportunities. Performance Improvement results in implementation of the plans and establishment of long-term, self-supporting mechanisms to sustain the effort after the formal end of the MIP.

APPROACH: In December 1990, under the direction of the U.S. Water Conservation Laboratory (USWCL), a Management Improvement Program was initiated by six agencies interested in testing the MIP methodology (see figure 2 for a list of all participating agencies). From April 1991 to January 1994, a demonstration project was carried out in the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) in central Arizona. The process was guided by a Management Team with input from the MIP partner agencies. In January 1994, the MIP Management Team ended its formal leadership of the Demonstration MIP, and a local, grower-led, grower-interagency organization, the MSIDD MIP Coordinating Group (CG) assumed the responsibility of leading ongoing and future collaborative initiatives in the MSIDD area. An evaluation report[1] of the outcomes and learnings of the demonstration project was published in October 1994.

[1] *The Evaluation Report of the Demonstration Management Improvement Program in the Maricopa-Stanfield Irrigation and Drainage District Area*, U. S. Water Conservation Laboratory (hereafter called *Evaluation Report*).

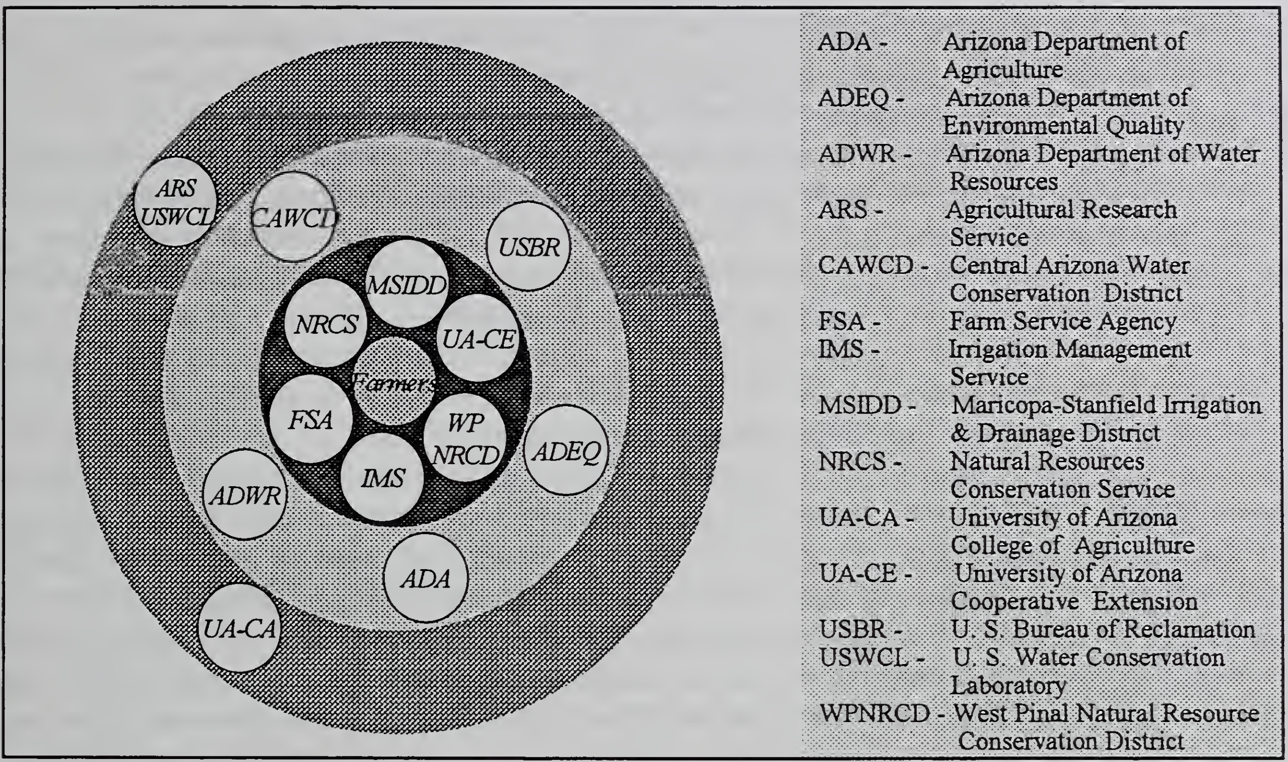


Figure 2. Schematic representation of entities involved in irrigated agriculture in the MSIDD-area. Entities were included as participants because of their potential to impact irrigated agriculture in the area. Moving outward from the growers, the first circle connects organizations or entities directly supporting agriculture in the MSIDD area; the second connects organizations with primarily regulatory missions although they may also have some support functions; and the farthest circle includes the two research and/or educational organizations involved. The original six agencies making up the Interagency MIP Coordinating Group were ARS, NRCS, USBR, ADWR, ADEQ, and Cooperative Extension.

Efforts over the past year have focused on the preparation of a series of manuscripts documenting the demonstration project. The purpose of the manuscripts is

- to provide a synoptic account of the various activities undertaken during the demonstration,
- to explain how the core MIP methodologies were employed, link the approach to general and organizational development theory, and summarize our methodological learnings,
- to summarize our findings relative to the agricultural system and provide an updated account of the impacts of the process on the project area, and
- to position the MIP with respect to other irrigation/natural resource managed change processes and provide guidelines for reapplication.

This documentation will include aspects of the process that posed problems. Some that were rooted in the early stages will be particularly important in reapplication considerations, most notably, securing and maintaining appropriate organizational mandates, establishing local leadership relatively early, and establishing procedures to new participants. (See "Annual Research Reports,"

1991through 1997, for earlier MIP activities and milestones.)

FINDINGS: In positioning the MSIDD-Area MIP within the context of other irrigation and organizational development efforts, both similarities and differences became apparent. Major learnings derived from this analysis are summarized below:

- The Action Research[2] components of the Demonstration MIP project proved critical to creating a new understanding of the agricultural system's performance among stakeholders. This understanding promoted some initial changes in on- and off-farm management practices, as reported in the *Evaluation Study*. The current range of impacts and their implications to area-wide resource management, though apparent, is difficult to quantify.
- The Demonstration MIP was successful in creating a framework for farmer-agency collaboration, as demonstrated by the various collaborative activities that evolved in the project area, beginning early and continuing after the formal demonstration project.
- The literature often reports that it is difficult to involve the general farmer population in agricultural change projects. In the MSIDD MIP, farmer participation was acknowledged as critical, and all farmers were welcomed. However, general farmer participation solicited directly was to share and to gain an understanding of the *Diagnostic Analysis* (*DA)* and *Evaluation Reports* and to prioritize program opportunities identified in the DA. Otherwise, a core group of about 12 farmers participated in planning and implementation activities and served well for that purpose. The disadvantage of this relatively small number of farmers is that, even with a few post-demonstration additions, it provided a small pool for ongoing MIP CG leadership and programs.
- Interest in farmer-agency activities has diminished over the last year, primarily because of the loss of institutional memory as former participants leave the area for new professional assignments. Relevant literature, reinforced by events in the project area, suggest that organizational transitions are an important challenge to multi-stakeholder organizations. External facilitative support may be needed during the first few years of the organization's life to establish a continuing onboarding process for new members and to maintain an overall awareness of purpose.

In addition to exhibiting important characteristics of past irrigation organizational change efforts, the demonstration project also contributed to the body of knowledge in important ways:

- A complete analysis, planning, and implementation cycle was planned, carried out, and evaluated, which previously had not been done using an explicitly phase-oriented model in an interdisciplinary, interagency approach.
- The conditions in the MSIDD area contrasted sharply from those in irrigation organizational development efforts described in the literature:
  - While earlier models primarily involved small, impoverished farms, those in the MSIDD area, by Third-World standards, were large and affluent, and, on average, the farmers had more years of education.
  - The objective of many of the overseas efforts was to form or empower user groups and involve those groups in the management of the water delivery system; in the MSIDD area, the grower

[2] The Action Research process originates from the social sciences and involves contributors of data in the data's interpretation. Its purpose is to promote individual or organizational change.

organization, i.e., irrigation district, was already in place. The challenge to the irrigation district then became the transition from water deliverer to water resource manager. Evidence of attitude changes are reflected in MSIDD's involvement in interagency activities, the redefinition of its mission statement, and the adoption of new client-oriented practices.

- The MSIDD infrastructure was new and modern. No infrastructural improvements were anticipated in the district. Much of the expected impact was in the form of improved management. Outcomes verified this initial assumption (see *Evaluation Report*).

In addition to organizational impacts, there is evidence that the MIP approach is being used successfully by former individual participants in the demonstration project, most notably in ARS and NRCS.

INTERPRETATION: Relevant literature suggests that the kind of cultural change advocated by the MIP does not happen quickly, usually taking from five to seven years. Therefore, while the impacts of the MIP have been evident in the form of a more farm-oriented delivery service by the irrigation district, the interaction of support and regulatory agencies, and grower-centered activities, the institutional future of the MIP in the MSIDD area is uncertain. It is important to recall, however, that the purpose of the Demonstration MIP was to test the process rather than to address specific needs in the project area. In future need-specific applications, funds would be pledged early on to support initiatives and would, therefore, reinforce the stakeholders' sense of purpose and commitment to the MIP process.

From a research standpoint, the MIP was recognized from the outset as long-term, high-risk research. Its value as a research project has been borne out in its extension of organizational development and change process theory, specifically related to agricultural systems; identification of technology needs; and development of technology transfer processes.

In terms of public need, the MIP responds to widespread calls for cooperative efforts at the local level. More recently, in the preliminary report of the Riley Memorial Foundation Regional Workshops on working toward common goals, dated May 8, 1998, two of the four "Challenges" concerned the need (1) to clarify the confusion about roles of agricultural support agencies and (2) to adopt organizational structures and procedures conducive to partnerships. Of the more than 100 cooperative projects presented regionally, the MIP was one of four presented to departmental and agency representatives in a culminative workshop in Washington, DC, in January 1998.

FUTURE PLANS: The research phase of the MIP has been completed. Work will focus on completion of a paper series for a special issue of *Irrigation and Drainage Systems (IDS)*. The *Evaluation Report*, together with the *IDS* series, can substantially guide future MIP applications, and members of the MIP Team will be available for advice. Future research will focus more on the technical details of irrigation system assessment and use of the data to improve system management and performance.

COOPERATORS: Cooperators include entities in figure 2, plus Wayne Clyma, Colorado State University; and David B. Levine, Management/Team Building Consultant, Washington, DC.

IRRIGATION CANAL AUTOMATION

A.J. Clemmens, Supervisory Research Hydraulic Engineer; R.J. Strand, Engineering Technician; E. Bautista, Agricultural Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: Modern, high-efficiency irrigation systems require a sufficiently flexible and stable water supply. Open-channel water delivery distribution networks are typically manually controlled and not capable of providing this high level of service. Stable flows can be achieved when little flexibility is allowed since canal operators can force canals flows to be relatively steady. Allowing more flexibility increases the amount of unsteady flow and leads to more flow fluctuations to users.

Most canal systems operate with manual upstream control. The disadvantage of this system is that all flow errors end up at the tail end of the system. In some canals, supervisory control systems are used to try to match inflows with the expected outflows. Because this adjustment is done by trial-and-error, pool volumes and water levels can oscillate until a balance is achieved. In canals with large storage volumes, these fluctuations may have little impact on deliveries. Smaller canals with insufficient storage need more precise downstream control methods than are currently available. Development of improved canal control methods requires convenient simulation of unsteady flow by computer. Many computer models of unsteady canal flow have been built in the last twenty years, some very complex and expensive, designed to model very complicated systems. Only recently have these programs been geared toward canal automation so that simulation of control algorithms could be made efficiently.

The objective of this research is to develop tools to promote the adoption of improved canal operating methods. This includes development and testing of canal control algorithms, development of necessary sensors and hardware, development of centralized and local control protocols, refinement of simulation models needed for testing these methods, and field testing of algorithms, hardware, and control protocol.

APPROACH: A Cooperative Research and Development Agreement between ARS and Automata, Inc., was established for the purpose of developing off-the-shelf hardware and software for canal automation, i.e., plug-and-play. We will work closely with Automata in the application and testing of this new hardware and software, shown schematically in Figure 1.

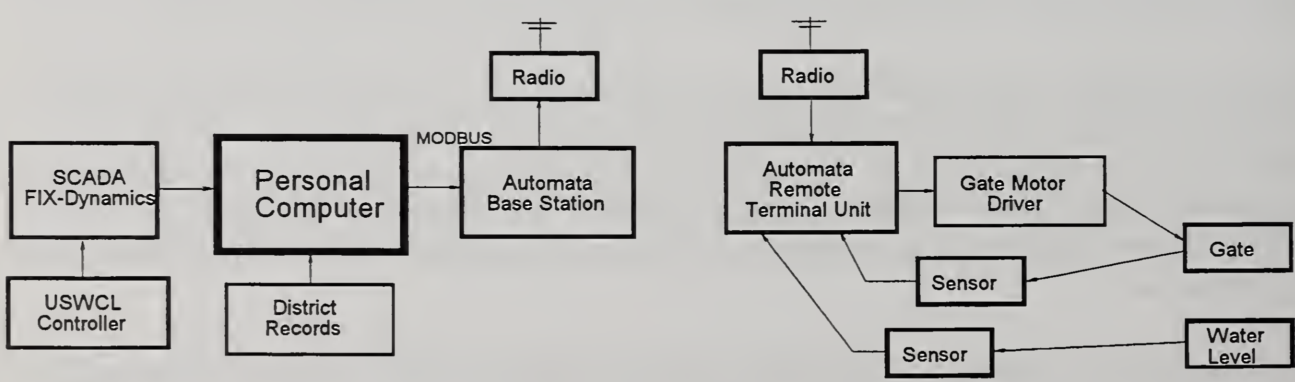


Figure 1. Canal automation system components.

The system is controlled from a personal computer at the irrigation district office. A Supervisory Control and Data Acquisition system (SCADA) is used by operators to monitor the irrigation system and to control gates remotely through radio communications. We plan to use a commercial SCADA package from Intellution, Inc., called Fix Dynamics. Standard MODBUS communication protocol will be used to communicate between Fix Dynamics and Automata's Base Station. Eventually all communications in the system will use MODBUS. The USWCL canal control scheme logic (USCWL controller) will be interfaced with Fix Dynamics. The research approach will be to use simulation models to test and further develop various control schemes that can be used within the proposed automation system. The hardware and software components will be assembled and made compatible in the field. Finally, the combined hardware and software automation system will be tested in the field.

FINDINGS: Canal control problems are caused by a mismatch between pool inflows and outflows and/or incorrect pool volumes. Some of these problems result from the travel times required for flow changes to be transmitted through the system. Canal controllers can be developed with only an understanding of wave travel times and pool volume relationships. This greatly simplifies the problem of controller development. Then, canal control becomes a problem of controlling both flow rate and pool volume, the latter reflected by water level deviations.

Simulation is an important tool for the development and testing of canal controllers. The simulation software program CANALCAD now allows the control subroutines to have global access to simulation variables and thus the ability to program centralized control schemes. This has now been utilized to test various canal algorithms for the ASCE canal automation test cases.

Most canal system are operated by routing known flow changes from the upstream to the downstream end. Complex hydraulic routing schemes, such as gate-stroking, have been developed to route the scheduled changes through the canal system. These routing schemes are not very robust, and steady state errors can be introduced if the hydraulic characteristics of the canal change. Figure 2 shows the deviations from the setpoint using gate stroking for the scheduled flow changes of the first four pools of ASCE test case 1-1 under untuned conditions (i.e., different Manning's *n*, gate discharge coefficients, and scheduled offtake changes). It can be seen that, in most cases, the water levels do not return to their original values.

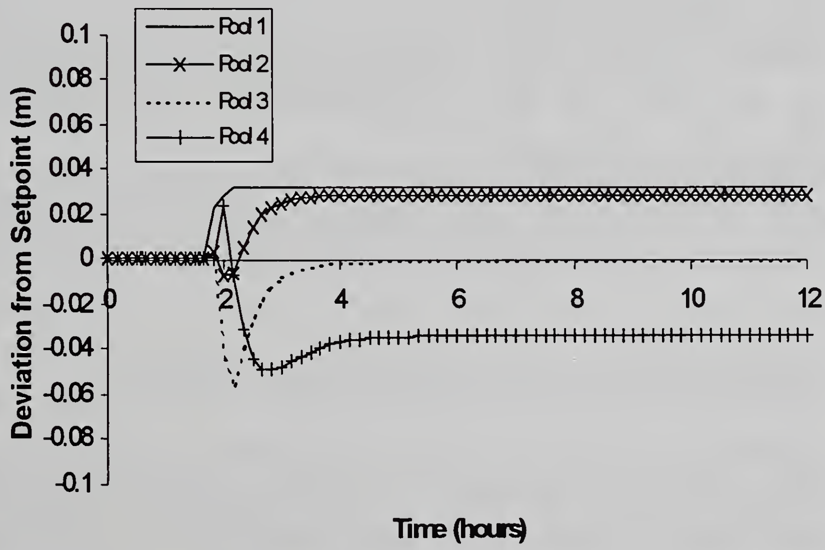


Figure 2. Deviations from the setpoint using gate stroking for the scheduled changes of ASCE test case 1-1 under untuned conditions.

The complex hydraulic routing schemes are difficult to implement in practice and can result in unacceptable inflow hydrographs. A much simpler approach to flow routing has been developed based on simple relationships between pool volume, flow rate, and wave travel times. The assumption behind this method is that if the correct volume is applied and inflow matches outflow, the pool will eventually stabilize itself with the correct volume and flow rates. Simulation results have shown that this is an acceptable approximation to the more complex solutions.

As shown in figure 2, routing schemes cannot adjust for unknown errors in flow rate or unexpected demand changes. Downstream feedback water-level control systems, such as classical proportional-integral (PI) control, are needed to handle these conditions. Many of the existing single-pool feedback controllers make corrections in gate position as a function of errors in the downstream water level. When there is only one pool in the system, the appropriate controller constants can be found by a simple trial and error technique. When applied to a series of canal pools, the control system becomes a series of independent controllers that interfere with each other because of the hydraulic interaction between the pools. In this case, tuning the control system becomes a much more difficult task that depends not only on the hydraulic interactions between the pools but also on the flow rate passing through the pools. Because of these drawbacks, these controllers have not been highly successful in practice.

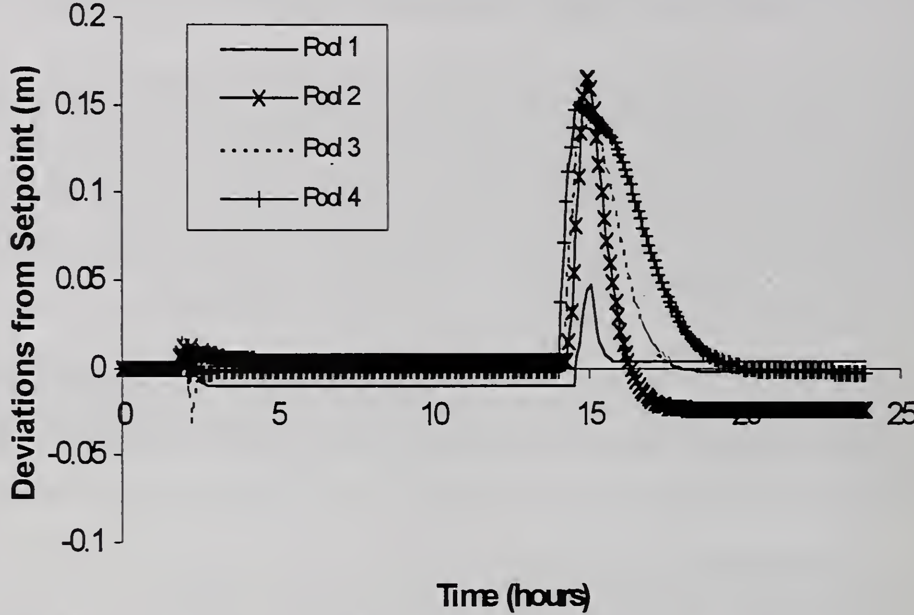


Figure 3. Deviations from the setpoint for proportional-integral control of ASCE test case 1-1 under untuned conditions.

Figure 3 shows the how well the classical PI controller can handle both the scheduled (at 2 hours) and unscheduled (at 14 hours) offtake changes for the ASCE test case 1-1 under untuned conditions (only first four pools shown). The advantage of prescheduling known offtake changes is clearly seen in figure 3. In both cases, the feedback control system brings the water levels back reasonably close to the set points after a few hours. The water levels will not exactly return to their original values because of a minimum gate movement constraint imposed on the gates. However, the deviations are less than those shown in figure 2, where no feedback control is used.

Simulation testing suggests that control of gate flow rate rather than gate position provides more effective control. To a degree, control of flow rates decouples the interactive effects between canal pools. It simplifies the problem since the gate hydraulics and pool dynamics can be treated separately.

A simplified model of canal transients was proposed to deal with pool dynamics for this class of controllers. This integrator-delay model divides each canal pool into two segments: a downstream segment that represents backwater behind the control or check structure, and a normal-depth segment. The downstream segment can be modeled as a reservoir, where inflow-outflow differences result in changes in volume and changes in water level according to its surface area. The upstream segment contains a delay time for the flow to arrive from the upstream end to the downstream end or reservoir segment. These two properties, delay time and reservoir surface area, are all that is needed to design the feedback controller. This control scheme has been successfully tested on the Arizona Canal for the Salt River Project. (See details in previous annual reports).

We are in the process of installing the canal automation system on the WM canal at the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) using Automata hardware. The new Remote Terminal Units (RTUs), gate position sensors, and base station have been installed and are communicating with one another. Some programming has been done on the RTU gate movement software, but more programming remains to be done. Initially, flow control functions will be carried out at the base station, leaving only the gate movement functions at the local RTU level. As the flow control functions are refined, they will be migrated to the local RTU environment to operate in a standalone fashion.

We are also interfacing the automation system with a commercial SCADA package, Fix Dynamics by Intellution, Inc. This interface consists of two components. The first is an ActiveX link that will enable operators to interact with the USWCL control functions. The second is an SQL link between the USWCL controllers and the FIX process database. This link will allow the control functions to interact with the RTUs without affecting the supervisory control capabilities of the operators. The operator interface will be updated automatically with the results of the supplemental data requests issued by the USWCL controllers. The system should be ready for testing in early 1999.

INTERPRETATION: The feasibility of a plug-and-play type canal automation system looks promising. Ensuring proper functioning of the system for a given canal will still require some engineering analysis to determine hydraulic properties and controller constants so that the automation performs adequately.

FUTURE PLANS: Programming for the RTU and base-station software will be completed over the next year. Field testing will begin with simple controllers. More complex controllers will be tested as they are developed. Work will continue on the development of feedback and disturbance controllers that perform better under unusual circumstances. A lateral canal with properties somewhat different from the WM canal will be selected for future analysis and testing of control algorithms.

COOPERATORS: Lenny Feuer, Automata, Inc.; Gary Sloan, MSIDD; Ken Taylor, CAIDD; Jan Schuurmans, Loughborough University, England; Dave Rogers, USBR, Denver; Charles Burt, Cal Poly; Bob Gooch, Salt River Project; Victor Ruiz, IMTA, Cuernavaca, Mexico; Pierre-Olivier Malaterre, CEMAGREF, Montpellier, France.

CANAL AUTOMATION PILOT PROJECT FOR SRP'S ARIZONA CANAL

A.J. Clemmens, Supervisory Research Hydraulic Engineer; E. Bautista, Agricultural Engineer; R.J. Strand, Engineering Technician; and B.T. Wahlin, Civil Engineer

PROBLEM: The Salt River Project (SRP) has a long history of being progressive in the management of its water distribution system. SRP's Roosevelt Dam was the first to be built under the Reclamation Act of 1902. The district also took control of the distribution network from the Bureau of Reclamation in 1917, to improve service to its water users. SRP developed its own supervisory control system in the mid 1960s, covering its entire network of main canals. In the 1980s, SRP embarked on an intensive water measurement program to reduce unaccounted water losses. With the conversion from agriculture to large urban water users, water quality is becoming a more important issue, and supervisory control operators are spending more and more of their time on such issues (e.g., maintaining acceptable water quality at the inlet to city water treatment plants). In the early 1990s, SRP constructed a new operations center with a state-of-the-art SCADA (Supervisory Control And Data Acquisition) system.

Studies in the 1970s by Zimbelman suggested that SRP's main canals could be operated with automatic downstream feedback control. Significant advances have been made in methods for canal automation with feedback control since then. The objective of this project is to determine the feasibility of implementing canal automation within SRP's distribution network.

APPROACH: A pilot project was initiated to develop and test a canal control algorithm on a portion of SRP's canal system, and to recommend whether it should be implemented. This pilot project is an SRP in-house research and development project, with cooperation from the U.S. Water Conservation Laboratory. The purpose of the project is to improve service, reduce operating costs, and improve SRP's stewardship of resources. The upper portion of the Arizona Canal (Figure 1) was chosen as the study site. This section includes 5 pools, separated by check structures, and includes a major branch point at the heading of the Grand Canal.

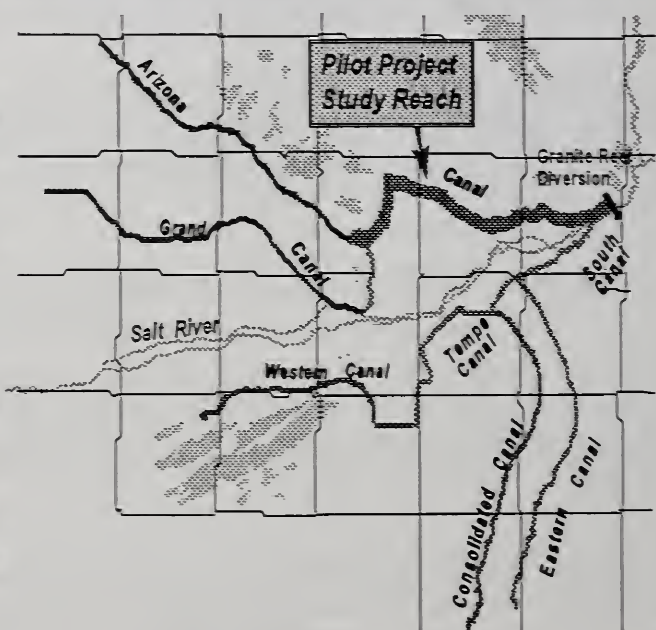


Figure 1. Layout of SRP's canal network.

Phase I of this pilot project consisted of development of an automatic control system and simulation studies to test its ability to control water levels on the upper Arizona Canal. First, the hydraulic properties of the canal pools were determined. Then the control algorithms were interfaced with the Mike-11 unsteady-flow open-channel simulation model. (SRP uses this software to model water quality on its canals.) SRP water masters developed a series of scenarios to test the automatic control system under simulation. Because the head-

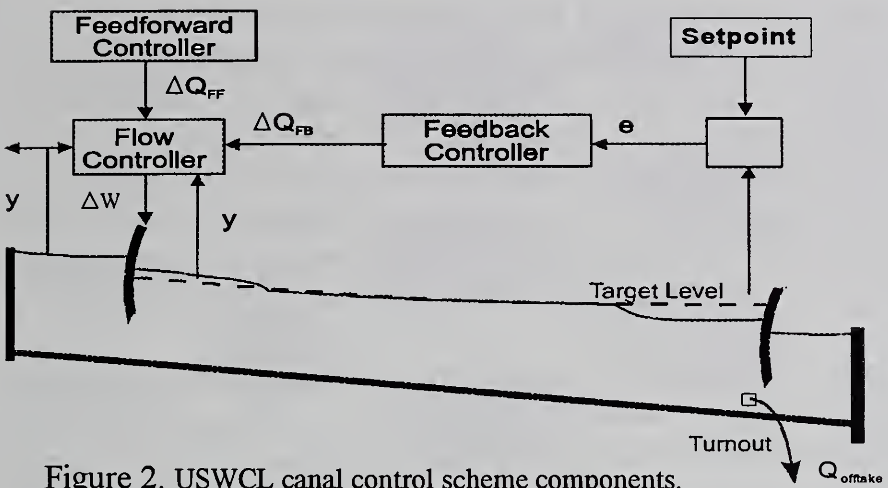


Figure 2. USWCL canal control scheme components.

discharge relationships of gates in the field are not precisely known, realistic errors were imposed on the flow controller within the Mike-11 simulations.

In view of the promising results, SRP decided to continue with the next phase. Phase II of the pilot project, which is currently underway, is to program the canal automation system into SRP's computing environment. During Phase III, the system will be tested in real time. If successful, SRP will implement the automatic control system on its entire canal network. The proposed canal control scheme, shown in Figure 2, has three main components: 1) downstream water-level feedback control to handle disturbances or errors in flow rate, 2) open-loop feedforward routing of scheduled or measured offtake flow changes, and 3) check structure flow-rate control.

Figure 3 summarizes the interfaces in SRP's current manual control system. Currently, the water-masters serve as the interface between the water orders and the canal check structues. In addition to being responsible for developing the operational schedule and providing manual feedback to the system, they must also determine if short notice flow change requests (red changes) can be satisfied, determine whether abnormal flow conditions are occurring on the canal (due to, for example, an unannounced offtake shutdown), and respond to customer and field operator complaints.

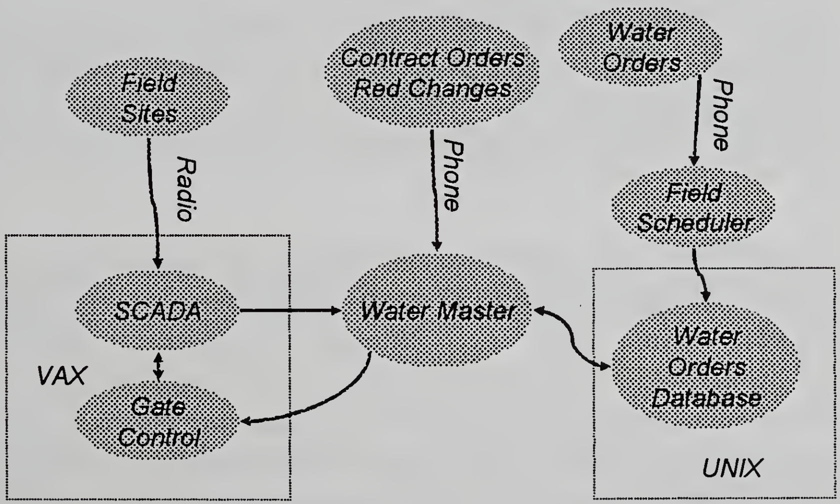


Figure 3. Diagram of SRP's current operations.

FINDINGS: The control logic was coded as Mike-11 subroutines to provide feedforward, feedback, and flow control functions (i.e., actually to change gate positions and inflow or make demand changes) from Mike-11 generated water levels. This model was also used to determine the response of canal pools to upstream flow changes. This canal response information was then used to develop the feedback control model and its coefficients.

SRP's test scenarios were used to examine the performance of the various controllers developed. The flow control function was used in all cases, either with perfect information (perfect flow control) or with a difference in the gate head-discharge relationship between the unsteady simulation model and

the flow control function. Some of these were examined with feedback only, feedforward only, or combined feedback-feedforward. Several of the tests represented typical daily variations in demand. A number of other tests were representative of emergency conditions, with large flow changes, failed gates, etc. In general, small flow changes (e.g., < 1 m^3/s) could be handled adequately with feedback control only (no feedforward). With feedforward control alone, the water levels drifted away from the set points over time. Large flow changes (e.g., > 4 m^3/s) required feedforward control with anticipation of the flow change ahead of time. Otherwise, the water levels deviated substantially from the setpoint for long periods of time (i.e., hours). These results were not unexpected.

To determine whether canal automation could improve current manual operations, we collected data on actual operations from a three day period. We used Mike-11 simulations to compare water level and offtake flow variations under automatic control with actual manual operations. Results suggests that the automatic control system can do as well or better than manual control. Figure 4 shows that the controllers requested upstream flow changes that were similar to that requested by manual operators, but both differed from the scheduled demand changes.

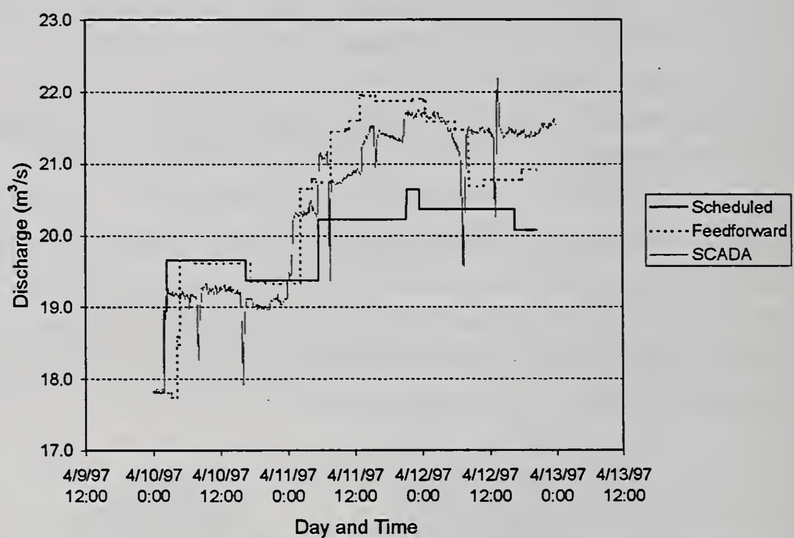


Figure 4. Comparison between manual and automatic operations

INTERPRETATION: Based on the analysis to date, it appears that canal automation (remote computer control) has some real potential for improving canal operations over supervisory (manual remote) control. The magnitude of unscheduled flow changes that can be allowed is still limited by the canal's hydraulic properties. Automation itself can not fully overcome these limitations.

FUTURE PLANS: SRP has funded the second phase of this project, in which we will program the automatic control system into their SCADA computer. Once this has been completed, the system will be tested on-line. There are three main components. The feedforward controller will be linked to SRP's water ordering worksheet. Water orders entered into the computer (an existing practice) will be used to schedule check gate flow changes upstream to Granite Reef Diversion so that the order can be satisfied on time. The program will tie into SRP's existing water ordering and billing database. The feedback controller will take water levels from the SCADA database and determine needed changes in check gate flows (i.e., it changes the inflow to each pool to satisfy downstream demand). The feedback and feedforward flow changes are sent to the autocontrol function for each check gate. The autocontrol system will adjust check gate positions to maintain the target flow rate.

Figure 5 depicts how the proposed control system will be interfaced with SRP's current computer

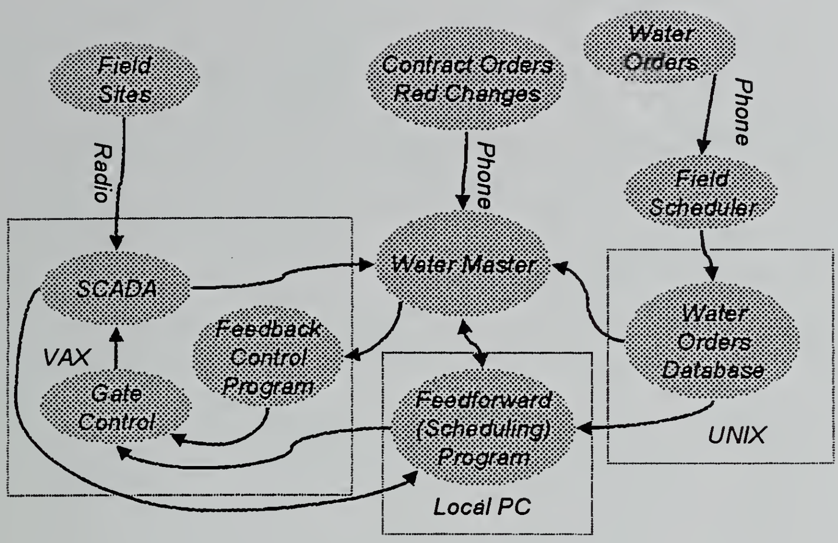


Figure 5. Diagram of proposed SRP operations with canal automation

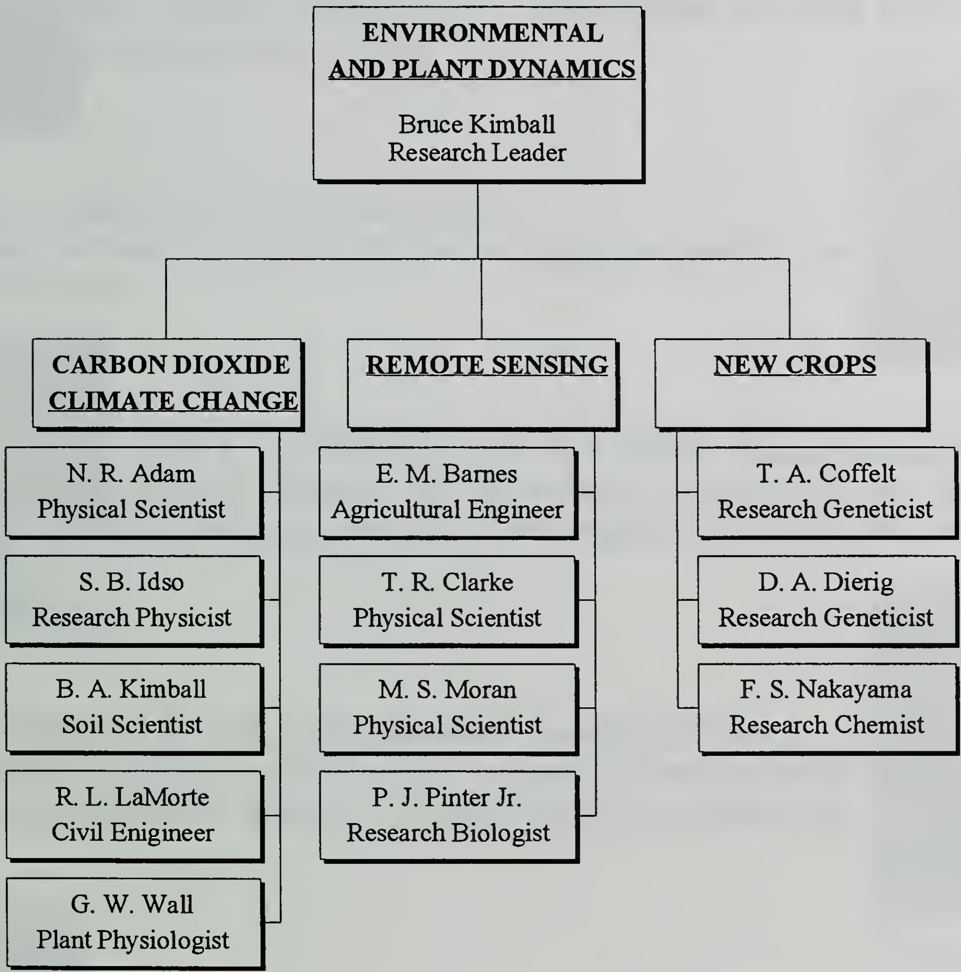
environment. The feedforward and feedback subsystems will provide flow change requests to the flow control component. SRP currently has a flow control system for a few of its supervisory laterals, but this system has to be upgraded to handle the automatic control system needs. The feedforward control componen will be initially run as a process in a PC environment but it is anticipated that it will eventually be integrated into the water ordering program (UNIX). Output from both the feedforward and feedback processes will be available to the water masters for their review and the water masters will still be able to issue flow change commands directly.

The pilot project's objectives are to test the feasibility of the control system and not full implementation. However, to test its potential fully, some level of implementation is required. The feedforward routing of flow changes is the highest priority for SRP's head of operations. The feedforward scheme accumulates water demands at lateral headings from the downstream to the upstream end of each canal. Therefore, even though full automation is being developed for only the upper Arizona Canal, the feedforward component is being developed for the entire north side (entire Arizona and Grand Canals), so that all downstream demand changes can be included. Initially the feedforward routines will access the SRP database and produce a hard copy of the suggested gate flow changes with time for operators to review and implement manually. Some training of watermasters will be necessary.

COOPERATORS: Robert Brouwer, Lennart Silvis, and Marente Brouwer, Delft U. of Technology, The Netherlands; Jan Schuurmans, Loughborough University, England; Bob Gooch, Joe Rauch and Grant Kavlie, Salt River Project.

E&PD Management Unit

E&PD Organization



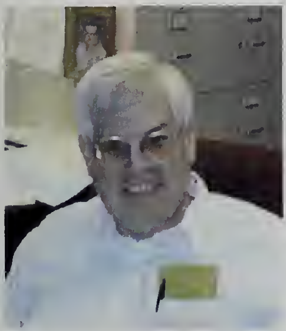
Mission

The Environmental and Plant Dynamics Research Group seeks to develop optimum resource management strategies for meeting national agricultural product requirements within the context of possible changes in the global environment. There are three main research thrusts: The first is predicting the effects of the increasing atmospheric CO_2 concentration and climate change on the yield and water use of crops in the future. The second thrust seeks to develop remote sensing approaches for observing plant conditions and biophysical processes which are amenable to large scale resource monitoring using aircraft- and satellite-based sensor systems. The third research thrust is to develop new industrial crops with unique high value products and lower water requirements for commercial production within the context of changing environments.

E&PD RESEARCH STAFF

EDWARD M. BARNES, B.S., M.S., Ph.D., Agricultural Engineer
Remote sensing applications for farm management; consideration of approaches that integrate remotely-sensed measurements with crop growth models and decision support systems.

THOMAS R. CLARKE, B.A., Physical Scientist
Remote sensing for farm management, thermal and optical radiometry, and instrument calibration.

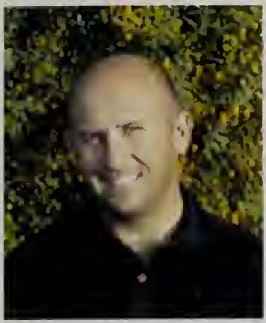


TERRY A. COFFELT, B.S., M.S., Ph.D., Research Geneticist-Plants
Breeding, genetics, and germplasm evaluation of new crops--guayule, lesquerella, and vernonia; development of acceptable production practices.

DAVID A. DIERIG, B.S., M.S., Ph.D., Research Geneticist-Plants
Breeding, genetics, germplasm collection and evaluation of new industrial crops with unique, high-value products, including lesquerella, vernonia, and guayule.

SHERWOOD B. IDSO, B.S., M.S., Ph.D., Research Physicist
Effects of atmospheric CO_2 enrichment on biospheric and climatic processes.

BRUCE A. KIMBALL, B.S., M.S., Ph.D., Research Leader for E&PD and Supervisory Soil Scientist
Effects of increasing atmospheric CO_2 and changing climate variables on crop growth and water use; free-air CO_2 enrichment (FACE), and CO_2 open-top chambers and greenhouses; micrometeorology and energy balance; plant growth modeling.

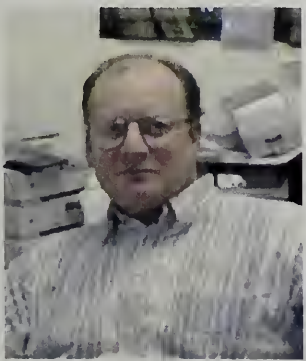


ROBERT L. LaMORTE, B.S.E., Civil Engineer
Instrumentation, operation and data collection for the control of atmospheric CO2 in global change experiments on agricultural crops.

M. SUSAN MORAN, B.S., M.S., Ph.D., Physical Scientist
Estimation of soil moisture and evapotranspiration; detection of physical and biological stress in plants; and evaluation of energy and water balances at local and regional scales utilizing models and remote sensing techniques.

FRANCIS S. NAKAYAMA, B.S., M.S., Ph.D., Research Chemist
New crops such as guayule (for latex rubber and resin), lesquerella (hydroxy fatty acid) and vernonia (epoxy fatty acid); including extraction and analytical techniques for the various components; Editor-in-Chief of Industrial Crops and Products, an International Journal.

PAUL J. PINTER, JR., B.S., M.S., Ph.D., Research Biologist
Applications of remote sensing technology to management of agricultural resources and research in plant sciences; effects of elevated CO_2 on biophysical properties of plants.



GERARD W. WALL, B.S., M.S., Ph.D., Plant Physiologist
Derivation of experimental databases to quantify growth, development, and physiological response of agronomic crops to full-season CO_2 enrichment; development of deterministic and stochastic digital simulation models of the soil-plant-atmosphere continuum in response to a CO_2 enriched environment.

PLANT GROWTH AND WATER USE AS AFFECTED BY ELEVATED CO_2 AND OTHER ENVIRONMENTAL VARIABLES

CONTENTS

PLANT GROWTH AND WATER USE AS AFFECTED BY ELEVATED CO_2 AND OTHER ENVIRONMENTAL VARIABLES

MISSION

To predict the effects of elevated CO2 and climate change on the photosynthesis, growth, yield, and water use of crops under optimal and limiting levels of water and fertility. Also, to measure these effects at controlled levels of environmental variable and under natural conditions and to determine the impacts on host-insect relationships.

THE FREE-AIR CO_2 ENRICHMENT (FACE) PROJECT: PROGRESS AND PLANS

B.A. Kimball, Soil Scientist; P.J. Pinter, Jr., Research Biologist; G.W. Wall, Plant Physiologist; R.L. LaMorte, Civil Engineer; N.R. Adam, Plant Physiologist; and T.J. Brooks, Research Technician

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. This project seeks to determine the effects of such an increase in CO_2 and any concomitant climate change on the future productivity, physiology, and water use of crops.

APPROACH: Numerous CO_2 enrichment studies in greenhouses and growth chambers have suggested that growth of most plants should increase about 30% on the average with a projected doubling of the atmospheric CO_2 concentration. However, the applicability of such work to the growth of plants outdoors under less ideal conditions has been seriously questioned. The only approach that can produce an environment today as representative as possible of future fields is the free-air CO_2 enrichment (FACE) approach. Therefore, the FACE Project was initiated, and experiments were conducted on cotton from 1989-1991(Hendrey, 1993; Dugas and Pinter, 1994). Then, from December 1993 through May 1994 two FACE experiments were conducted on wheat at ample and limiting levels of water supply, with about 50 scientists from 25 different research organizations in eight countries participating. About 32 papers have been published (e.g., Kimball et al., 1995; Pinter et al., 1996) or are in press from these experiments, and more are being prepared.

However, one of the greatest uncertainties in determining the impact of global change on agricultural productivity, as well as on natural ecosystems, is the response of plants to elevated CO_2 when levels of soil nitrogen are low. Therefore, we conducted two additional FACE wheat experiments at ample and limiting supplies of soil nitrogen from December 1995 - May 1996 and December 1996 - May 1997. Funded by the Department of Energy through a grant to the University of Arizona, U.S. Water Conservation Laboratory personnel were major collaborators on the project and provided management support. In addition, soil cores and leaf samples were obtained and were stored frozen for later analyses of root biomass and soil nitrogen, photosynthetic proteins, and carbohydrates. Thanks to a grant from a NSF/DOE/NASA/USDA program (TECO II) plus ARS Temporary Global Change Funds, personnel to do these analyses were hired, and many analyses were conducted during this past year. Much data from many kinds of measurements made during these latter experiments have been analyzed during the past year, and manuscripts are being prepared.

Much of the CO_2 enrichment research that has been conducted in the past has been with C3 plants and relatively little with C4 crops such as corn, sugarcane, or sorghum. The neglect of C4s was because their photosynthetic process was known to respond relatively less to elevated CO_2. However, their stomata do partially close in elevated CO_2, thereby suggesting the possibility of some water conservation. Therefore, with grants (one to USWCL and one to the University of Arizona) from the NASA/NSF/DOE/USDA/EPA (TECO III) Program, we initiated a FACE experiment on

Figure 1. Aerial view of FACE sorghum field. North is at the top. Four replicate pairs of FACE and Control rings are shown numbered from 1 (east) to 4 (west). The FACE rings are the north rings in Reps 1 and 4 and south in Reps 2 and 3. Each ring is split into well-watered (Wet) and water-stressed (Dry) halves with a center berm/walkway as the divider. "Carry ditches" that convey irrigation water north from the concrete ditch at the south side of the field are also visible.

sorghum in July 1998, which is expected to end about the first part of December 1998. Our hypothesis is that there will be only a small enhancement of growth due to the FACE treatment when the plants have ample water, but under water-stressed conditions, there will be a substantial growth enhancement resulting from the water conservation due to the partial stomatal closure.

Between the wheat and sorghum experiments, we upgraded our FACE apparatus to conform with the latest designs from Brookhaven National Laboratory. This enhancement involved the use of pneumatic rather than electrical valves, addition of individual valves to all the vertical vent pipes in our Control rings, and installation of fiber-optic communications. We also moved from our old heavily soil-sampled field to an adjacent field, which involved installation of a CO_2 pipeline from the storage tank and of new power lines. We also switched from using a subsurface drip irrigation system to surface flooding because the flood system is more like farmer irrigation for sorghum and like rainfall.

Similar to the previous experiments, measurements included leaf area, plant height, above-ground biomass plus roots that remained when the plants were pulled, apical and morphological development, canopy temperature, reflectance, chlorophyll, light use efficiency, energy balance, evapotranspiration, soil and plant elemental analyses, soil water content, photosynthesis, stomatal conductance, grain quality, video observations of roots from minirhizotron tubes, soil CO_2 and N_2O fluxes, and changes in soil C storage from soil and plant C isotopes. Some soil cores for roots have also been obtained. As before, all of the data will be assembled in a standard format for validation of plant growth models.

FINDINGS: Analyses of the data from the FACE wheat experiments are underway, as reported by Adam et al., Wall et al., Wechsung et al., and Kimball et al. in this volume. Briefly, the results indicate that under the high nitrogen treatment, wheat grain yields were increased about 15% by

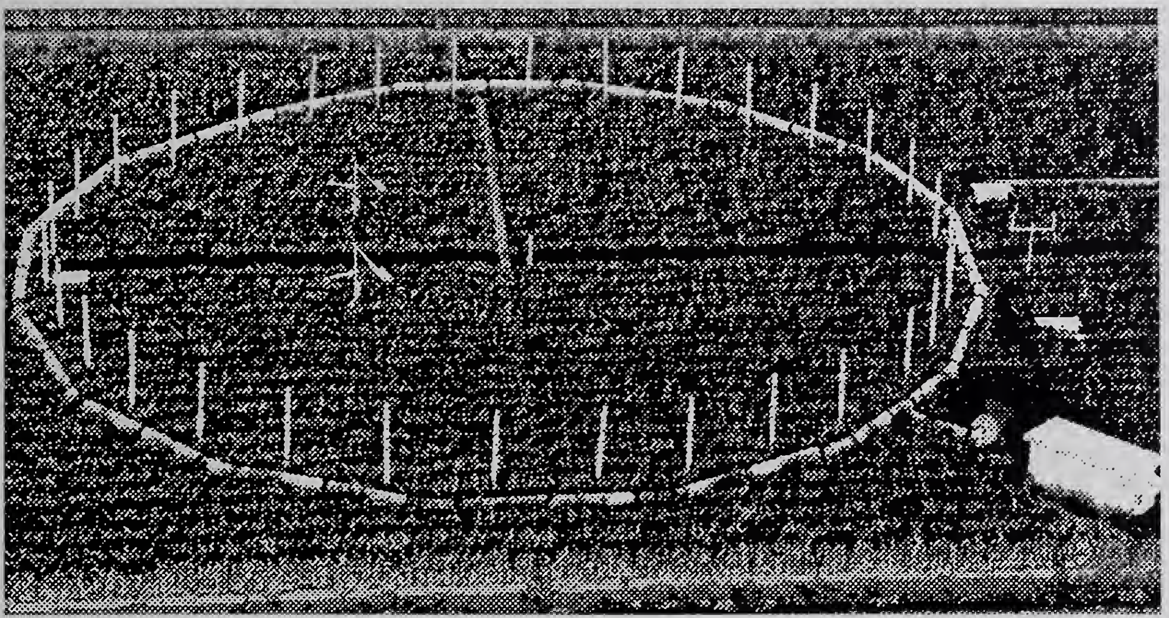


Figure 2. Aerial view of individual free-air CO_2 enrichment (FACE) ring in sorghum field.

FACE at 200 μmol/mol above ambient. At low nitrogen, yields increased about 12%. The low nitrogen treatment reduced yields about 20% at both levels of CO_2.

The FACE sorghum experiment is underway, as illustrated by figures 1 and 2, which are aerial views of the field and of an individual ring. As of this writing, the crop is growing well in spite of delays in getting started although cool fall temperatures are now slowing maturation, so frost danger looms. Also currently, an aggressive campaign is underway to minimize bird damage. One problem encountered with the FACE sorghum experiment is that relatively large irrigations have been required to get good distribution uniformity. The Trix clay loam soil in the field cracks severely when it dries. The first irrigation of the season after months of drying required about 275 mm to get coverage. This amount of water is more than planned for the Dry treatment for the whole season. Thus, only one additional mid-season irrigation was applied to the Dry plots, but it was about 175 mm in order to get coverage. Thus, the Dry plots have not been water-stressed as often as planned, so changes in the irrigation system will have to be made before the next crop.

INTERPRETATION: The data from the FACE wheat experiments suggest that with ample water, wheat production is likely to increase 10-15% by an increase in atmospheric CO_2 levels to 200 µmol/mol above current levels (about 370 µmol/mol). Moreover, in contrast to many chamber studies, our results suggest that the yield increases will occur even at low levels of soil nitrogen characteristic of the agriculture in developing countries and most natural ecosystems. Irrigation requirements may be unchanged or slightly reduced for future wheat production, provided climate changes are minimal.

FUTURE PLANS: Analyses and reporting of the results from the FACE wheat experiments will continue. Of course, the current FACE sorghum experiment will be completed. Then, with final year funding from the TECO III Program, a second FACE sorghum experiment will be conducted during the 1999 growing season (July-November). Again, the interaction of elevated CO_2 and soil water

supply on the growth, physiology, and water relations of this important world crop will be studied.

COOPERATORS:

Arizona State University, Tempe, AZ -- A. Webber, G. Wechsung, A. Cousins, D. Clark
Brookhaven National Laboratory, Upton, NY -- G. Hendrey, K. Lewin, J. Nagy
CSIRO Wildlife and Ecology, Lyneham, ACT, Australia -- M. Howden
Grassland Protection Research (USDA-ARS, Temple, TX) -- H. Johnson, H.A. Torbert
Kansas State University, Manhattan, KS -- R. Vanderlip
NASA-Goddard Institute for Space Studies, New York, NY -- F. Tubiello, C. Rosensweig
National Institute of Agro-Environmental Sciences, Tsukuba, Japan -- Y. Harazono, K. Kobayashi
National Soil Dynamics Laboratory, USDA-ARS, Auburn, AL -- S. Prior, H. Rogers
Northern Arizona University, Flagstaff, AZ -- G. Koch
Oak Ridge National Laboratory, Oak Ridge, TN -- J. Amthor
Potsdam Inst. for Climate Impact Research, Potsdam, Germany -- F. Wechsung, T. Kartschall, S. Grossmann, M. Bauer, J. Grafe, K. Waloszcyk
Università della Tuscia, Viterbo, Italy -- M. Badiani, A.R. Paolacci
Universitat Autònoma, Barcelona, Spain -- M. Estiarte, J. Peñuelas
University of Alberta, Edmonton, Alberta, Canada -- R. Grant
University of Arizona, Tucson and Maricopa, AZ -- S. Leavitt, M. Ottman, T. Thompson, A. Matthias, D. Williams, T. Brooks, J. Watson, R. Roth, D. Langston
University of Essex, Colchester, UK -- A. Ball, S. Long
University of Guelph, Guelph, Ontario, Canada -- A. Hunt
University of Illinois, Chicago, IL -- H. BassiriRad, J. Constable
University of Idaho, Moscow, ID -- L. Aiguo
University of Florida (USDA-ARS, Gainesville, FL) -- T. Sinclair
University of Wisconsin-Madison, Madison, WI -- J. Schleucher
U.S. Water Conservation Laboratory (USDA-ARS, Phoenix, AZ) -- B. Kimball, P. Pinter Jr., G. Wall, R. LaMorte, D. Hunsaker, F. Nakayama, F. Adamsen, E. Barnes, N. Adam
Vrie Universiteit of Amsterdam, Amsterdam, Netherlands -- A. Frumau, H. Vugts
Western Wheat Quality Laboratory (USDA-ARS, Pullman, WA) -- C. Morris

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Pinter Jr., P.J., Kimball, B.A., Garcia, R.L., Wall, G.W., Hunsaker, D.J., and LaMorte, R.L. 1996. Free-air CO_2 enrichment: responses of cotton and wheat crops. In G.W. Koch and H.A. Mooney (eds.), *Carbon Dioxide and Terrestrial Ecosystems*, Academic Press, San Diego. 215-248.

OSMOTIC ADJUSTMENT IN SPRING WHEAT GROWN IN A FREE-AIR CO_2 ENRICHED (FACE) ATMOSPHERE AND UNDER VARIABLE SOIL MOISTURE REGIMES

G.W. Wall, Plant Physiologist; B.A. Kimball, Supervisory Soil Scientist; P.J. Pinter, Jr., Research Biologist; S.B. Idso, Physical Scientist; and R.L. LaMorte, Civil Engineer

PROBLEM: Based on the Intergovernmental Panel on Climate Change (IPCC, 1996) atmospheric CO_2 concentration (C_a) is rising. Rising levels of C_a affect the exchange of CO_2 and H_2O between the atmosphere and the plant. But, an overall improvement in water relations in wheat may occur because of the direct effect of CO_2 in lowering stomatal conductance (g_s). Furthermore, greater carbon gains due to elevated CO_2 have resulted in an increase in root mass by 26% under well-watered and 28% under water-stress conditions (G. Wechsung et al., this volume), and root parameters such as length density, surface area, and thickness were increased by as much as 31% due to elevated CO_2, particularly under drought. Although elevated CO_2 increased the capacity of a wheat crop's fibrous root system to mine available soil moisture, the apparent root hydraulic conductivity -- flux of water from soil to plant per unit of water potential gradient from soil to atmosphere -- was 2% lower due to elevated CO_2. Consequently, lower water usage and greater capacity to mine soil moisture resulted in an improvement in water relations of spring wheat. Nevertheless, as a drought becomes more severe, drought tolerance mechanisms such as osmoregulation and alterations in the physical attributes of plant tissue [i.e. changes in cell wall extensibility (bulk modules of elasticity)] can also contribute to ameliorating the adverse effects of drought. These drought tolerance mechanisms vary, however, depending on whether plants are preconditioned to drought, and elevated CO_2 may affect this effect. Sionit *et al.*, (1980, 1981) showed that the rate of loss of turgor ($\Delta\Psi_P$) was lower due to elevated CO_2 because of a higher rate of osmotic adjustment($\Delta\Psi_O$), and consistent with the effect of CO_2 on $\Delta\Psi_O$, its effect on $\Delta\Psi_P$ was less during the second compared with the first dehydration cycle.

A good hypothesis to test, therefore, is that g_s in wheat does acclimate to elevated CO_2, thereby, enabling wheat plants to tolerate drought and that it does so because of an enhanced osmoregulatory mechanism. To assess the validly of this hypothesis, values of midday total leaf water potential (Ψ_T) were divided into their components (Ψ_O and Ψ_P) from anthesis until soft dough after two soil dehydration cycles occurred which preconditioned the crop to drought.

APPROACH: A field study on a hard red spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) crop was conducted in an open field at the University of Arizona, Maricopa Agricultural Research Center, located 50 km south of Phoenix, Arizona (33.1 °N, 112.0 °W). 'Yecora Rojo' was sown (180 plants m^{-2}) on 7-8 Dec. 1993 in an openfield. Following sowing, a FACE apparatus was erected on site to enrich the C_a of ambient air (~350 $\mu L\ L^{-1}$) to a 550 $\mu L\ L^{-1}$ treatment level (main-plot). A sub-surface drip tape irrigation system supplied a full irrigation (100% evaporative demand) and a 50% reduction in water supply (split-plot) treatment. A preplant application of nitrogen along with several chemigation applications provided a total of 233 kg ha^{-1} N. A preplant application of ~55 kg ha^{-1} P_2O_5 was applied. CO_2 enrichment occurred for 24 h per day from 50% emergence until

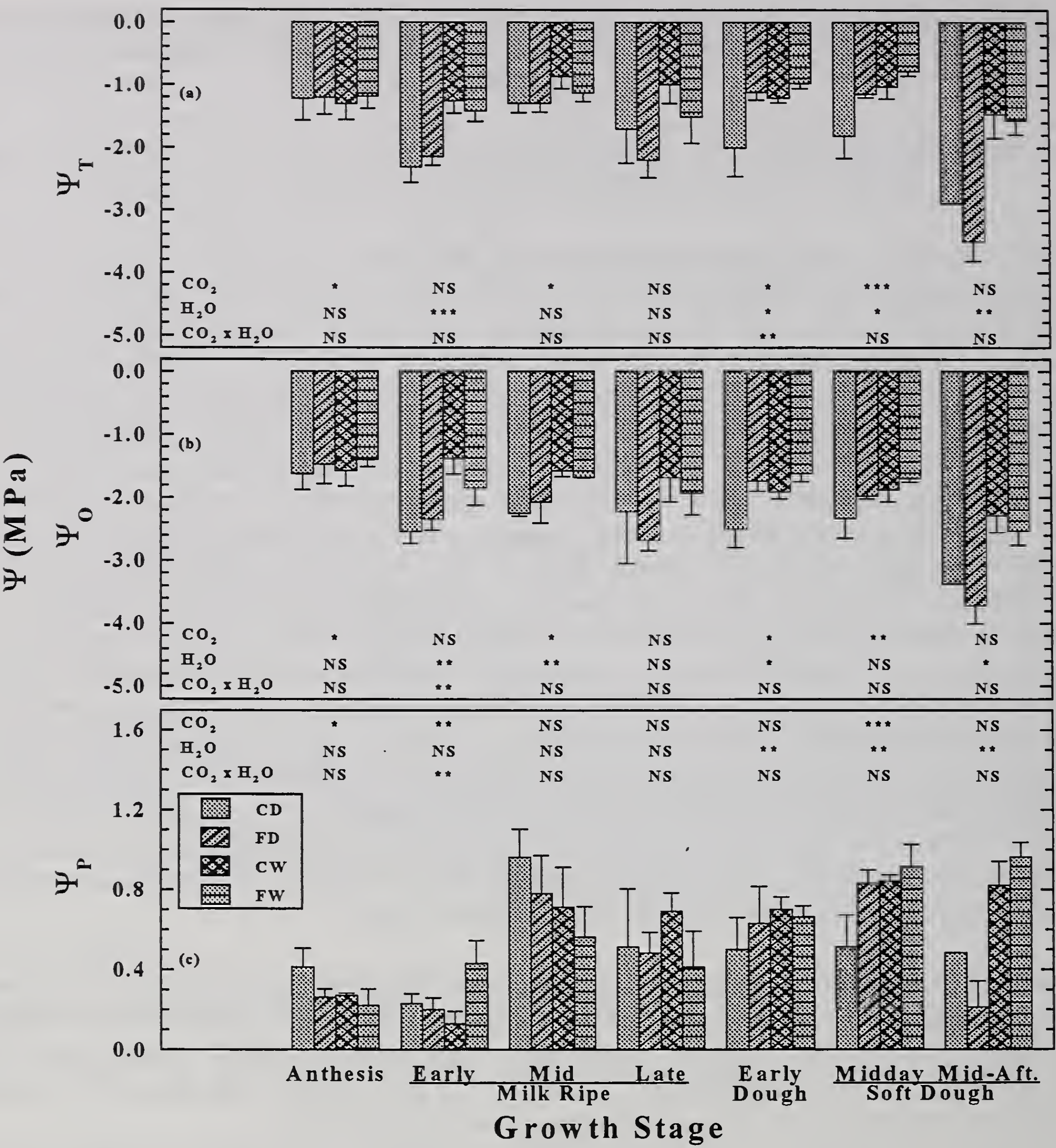

Figure 1. Mean total (Ψ_T) (a), osmotic (Ψ_O) (b), and pressure (Ψ_P) (c) potentials for fully-expanded sunlit flag leaves of wheat (*T. aestivum* L. cv. Yecora Rojo) measured with screen-caged thermocouple psychrometers at midday (12:30-13:45 MST) and at mid-afternoon (Mid-Aft.) (14:00-15:30 MST) on Zadok's growth stage given, which corresponds with day after planting 119, 129, 134, 143 and 147. Treatments include air enriched to 550 μmol mol^{-1} CO_2 using a free-air CO_2 enrichment (FACE) apparatus and ambient air (ca. ~370 μmol CO_2 mol^{-1}) (Control), and well-watered (Wet) and water-stress (Dry) plants: Control-Dry (CD); FACE-Dry (FD); Control-Wet (CW); FACE-Wet (FW). Error bars are based on one standard error from the mean. Source of variance for ANOVA include: carbon dioxide effect [(CO_2); Control:FACE; 370:550 μmol mol^{-1}]; irrigation effect [(H_2O: Dry: Wet; 50:100% replacement of evapotranspiration], and CO_2xH_2O effect. Levels of significance are ***, **,*, and NS for p≤0.05, p≤0.01, and p≤0.20, and not significant, respectively.

physiological maturity (December 28 - May 31). Screen-cage thermocouple psychrometers were used to measure midday Ψ_T and Ψ_O, whereas Ψ_P was derived ($\Psi_P = \Psi_T - \Psi_O$).

The measurements were done on the upper-most fully expanded leaves on six days from anthesis until soft dough (DAP 119-147) when values of soil matrix potential (Ψ_M) were at their most negative (-0.02 to -0.91 MPa for Dry and -0.01 to -0.21 MPa for Wet).

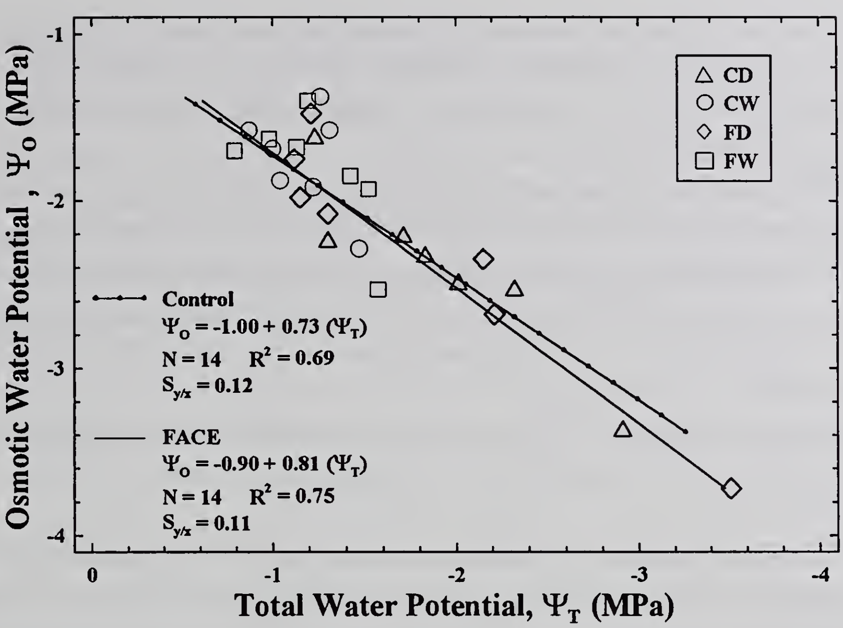

Figure 2. Regression of osmotic (Ψ_O) with total leaf water potential (Ψ_T) (i.e., rate of change in osmotic potential; $\Delta\Psi_O$) from anthesis until soft dough for fully-expanded sunlit flag leaves of wheat (*T. aestivum* L cv. Yecora Rojo) grow in air enriched to 550 µmol mol^{-1} CO_2 (FACE) and ambient air (ca. ~370 µmol mol^{-1}) (Control), and under well-watered (Wet) and water-stress (Dry): Control-Dry (CD); Control-Wet (CW); FACE-Dry (FD); FACE-Wet (FW). Summary statistics for a linear regression (N, number of observations; R^2, coefficient of determination; $S_{y/x}$, standard error of y given a value of x).

FINDINGS: CO_2 effect means for Ψ_T, Ψ_O, and Ψ_P ranged from -0.96 to -1.90, -1.47 to -2.37, and 0.17 to 0.86 MPa, whereas H_2O effect means ranged from -0.90 to -2.26, -1.45 to -2.58, and from 0.22 to 0.87 MPa, respectively (Figure 1). Across all growth stages, the overall mean Ψ_T, Ψ_O, and Ψ_P were 0.10 MPa more negative, 0.16 MPa less negative, and 0.01 MPa less positive, respectively, for Control compared with FACE, and 0.57 and 0.52 MPa more negative, and 0.12 MPa less positive for Dry compared with Wet. The rate of osmotic adjustment ($\Delta\Psi_O$) (standard error) was derived by regressing Ψ_O with Ψ_T; 0.73 (0.05) for Control and 0.81 (0.05) for FACE (p=0.20) (Fig. 2). Similarly, the rate of loss of turgor ($\Delta\Psi_P$) (standard error) was derived by regressing Ψ_P with Ψ_T; 0.18 (0.09) for Control and 0.16 (0.09) for FACE (p=0.20). An 11% increase in $\Delta\Psi_O$ resulted in an 11% reduction in $\Delta\Psi_P$ due to elevated CO_2. As values of Ψ_T became more negative with more negative values of Ψ_M, so did those of Ψ_O. The $\Delta\Psi_O$ was 11% lower for Control [0.73 (0.05)] compared with FACE [0.81 (0.05)] (p=0.20). When Ψ_M was at its most negative value of 0.91 MPa at soft dough on DAP 147, Ψ_O was more negative by 0.50 MPa at midday (Ψ_O was -3.2 in Control compared with -3.7 MPa in FACE). Conversely, as values of Ψ_T became more negative with more negative values of Ψ_M, Ψ_P became less positive (data not shown). The $\Delta\Psi_P$ was 11% higher in Control [0.18 (0.09)] compared with FACE [0.16 (0.09)] (p=0.20). When Ψ_M was at its most negative value of 0.91 MPa at soft dough on DAP 147, Ψ_P was more positive by 0.33 MPa (Ψ_P was 0.50 MPa in Control compared with 0.83 MPa in FACE).

INTERPRETATION: Under high C_a, g_s will decrease, thereby, increasing resistance to water vapor flux. Consequently, for comparable atmospheric and edaphic conditions, the leaf transpiration rate

will be lower due to elevated CO_2 as will the total water transport from root to shoot. Leaves grown in elevated CO_2, therefore, will maintain higher relative water content than ambient grown leaves. Hence, elevated CO_2 will enable a wheat crop to avoid drought by conserving water. But, as water becomes more limiting, elevated CO_2 will also enable a wheat crop to tolerate drought. An increase in $\Delta\Psi_O$ and a corresponding decrease in $\Delta\Psi_P$ will occur under elevated CO_2, presumably by an increase in the concentration of osmotica of photosynthetic origin in the vacuoles of the plant cell. The more negative values of midday Ψ_T in leaves growing under present-day C_a will induce stomatal closure earlier each day as the soil dries, whereas the less negative values of Ψ_T in C_a-enriched leaves will enable stomata to remain open even as the soil becomes more dry. Consequently, midday depression in photosynthetic rates will be less severe in leaves grown in elevated CO_2. Maintaining less negative values of Ψ_T in water-stressed leaves growing under high C_a will increase the likelihood that growth of organs will be at near optimal levels even if a soil moisture deficit exists.

FUTURE PLANS: The first of a two-year FACE experiment on sorghum (*Sorghum bicolor* L. Moench) was completed during the 1998 growing season. A second experiment will be conducted during the 1999 season. Preliminary results obtained during 1998 indicate that sorghum responded to elevated CO_2 in a similar manner as wheat by enhancing the rate of osmotic adjustment thereby lowering the rate of loss of turgor, particularly as drought became more severe.

COOPERATORS: See FACE cooperator listing given by Kimball *et al.* in this volume. Operational support was contributed by NSF/DOE/NASA/USDA Joint Program on TECO II (NSF 95-27 Grant IBN-9652614).

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ENERGY BALANCE AND EVAPOTRANSPIRATION OF WHEAT: EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) AND SOIL NITROGEN

B.A. Kimball, Soil Scientist; R.L. LaMorte, Civil Engineer; C. O'Brien, Research Assistant; D.J. Pabian, Associate Engineer; R. Suich, Physical Science Technician; P.J. Pinter, Jr., Research Biologist; G.W. Wall, Plant Physiologist; T.J. Brooks, Research Technician; D.J. Hunsaker, Agricultural Engineer; F.J. Adamsen, Soil Scientist; T.R. Clarke, Physical Scientist; and R. Rokey, Biological Technician Plants

PROBLEM: The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (***ET***), which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. Therefore, one important objective of the Free-Air CO_2 Enrichment (FACE) Project (See Kimball et al. this volume) is to evaluate the effects of elevated CO_2 on the ***ET*** of wheat and other crops.

APPROACH: We conducted four FACE experiments on wheat from December through May of the growing seasons 1992-3, 1993-4, 1995-6, and 1996-7. For the first two of these experiments, there was an additional water stress variable, but sufficient instrumentation was not available to measure ***ET*** in the water-stressed plots. The second two experiments were conducted at ample and limiting levels of soil nitrogen. This report presents a summary of the combined analyses of the energy balance measurements from all four seasons of the well-watered wheat at ample nitrogen and also from two seasons of well-watered wheat when soil nitrogen was limited. Additional details can be found in Kimball et al. (1994, 1995, 1999).

Briefly, the FACE apparatus consists of the following: Four toroidal plenum rings of 25 m diameter constructed from 12" irrigation pipe were placed in a wheat field at Maricopa, Arizona, shortly after planting. The rings had 2.5-m-high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings, and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots so that the CO_2-enriched air flowed across the plots no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to maintain desired CO_2 concentrations at the centers of the rings. For the first two wheat experiments, the FACE CO_2 concentration was set at 550 ppm by volume, while for the latter two it was elevated by 200 ppm CO_2 above ambient (about 360 ppm in daytime). For the first two experiments, the Control rings had the same piping at the FACE rings but no extra air flow. For the second two experiments, four matching Blower rings with similar air flow but no added CO_2 were also installed in the field.

In addition to the CO_2 treatments, varying soil nitrogen was also a factor in the second two experiments. Using a split-plot design, the main circular CO_2 plots were divided into semi-circular

halves, with each half receiving either High-nitrogen (N) (350 kg N/ha) or Low-N (75 kg N/ha in 1995-6: 15 kg N/ha in 1996-7) of ammonium nitrate (NH_4NO_3) fertilizer through the drip irrigation system.

The determination of the effects of elevated CO_2 on $\boldsymbol{ET}$ by traditional chambers is fraught with uncertainty because the chamber walls that constrain the CO_2 also affect the wind flow and the exchange of water vapor. Therefore, a residual energy balance approach was adopted whereby $\boldsymbol{ET}$ was calculated as the difference between net radiation, $\boldsymbol{R_n}$, soil surface heat flux, $\boldsymbol{G_0}$, and sensible heat flux, $\boldsymbol{H}$:

$$\lambda ET = R_n - G_0 - H$$

$\boldsymbol{R_n}$ was measured with net radiometers and $\boldsymbol{G_0}$ with soil heat flux plates. $\boldsymbol{H}$ was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. Air temperatures were measured with aspirated psychrometers, and crop surface temperatures were measured with infrared thermometers (IRTs) mounted above each plot. Fifteen-minute averages were recorded on a datalogging system. The net radiometers and IRTs were switched weekly between the FACE and Blower plots.

FINDINGS: There were small but consistent differences between the FACE and Control/Blower treatments at both High- and Low-N in the daily total fluxes of net radiation, $\boldsymbol{R_n}$, sensible heat flux, H, and latent heat flux, λET. Daily totals of soil heat flux , G_o, were very small (generally < 1 MJ $^{-2}$ day^{-1}), as expected. Daily FACE $\boldsymbol{H}$ tended to be about 0.7 MJ $^{-2}$ day^{-1} higher than Blower $\boldsymbol{H}$, which meant it was less negative on many of the days. This tendency was because the FACE plants were slightly warmer than the Blower plants during most of the daytime, and both FACE and Blower plants generally were cooler than the air except from about dawn until shortly after noon. (At High-N, the FACE foliage was 0.6 warmer and 0.1 °C cooler than the Blower foliage during day- and nighttime, respectively, while at Low-N, it was 1.1 and 0.1 °C warmer as determined from hourly averages during about 70 days between February and April, 1996.)

The slope of the regression line in figure 1A indicates that the FACE treatment decreased net radiation, $\boldsymbol{R_n}$, by about 1.3% [(1.000 - 0.987)*100 = 1.3%; ± S.E. of 0.6%] under Wet, High-N conditions. Under Low-N conditions, the reduction in $\boldsymbol{R_n}$ was similar (Fig. 1B). A decrease in $\boldsymbol{R_n}$ was expected because of the warmer temperatures in the FACE compared to the Blower or Control plots. However, at a surface temperature of 20 °C, a 0.6 °C canopy temperature increase would be expected to decrease $\boldsymbol{R_n}$ by 3.4 W/m^2, and such a decrease would be only about 0.5% of typical midday $\boldsymbol{R_n}$ values. Also under Low-N, the temperature increase was greater (1.1 °C during daytime), yet the $\boldsymbol{R_n}$ change was about the same (figures 1A and 1B). Therefore, canopy structure and/or leaf reflectance properties for short-wave radiation also must have been altered by the FACE treatment, and the amount of alteration was more in the Low- than in the High-N plots. Moreover, such changes were observed. Brooks et al. (1997) determined mean leaf tip angles and found that the FACE-Low-N canopy was more erectofile while the FACE-High-N was more planar. In 1992-3 and 1993-4 the FACE plots had a larger albedo from grain filling onward (although at heading the FACE plots were lower), which would have decreased $\boldsymbol{R_n}$ relative to the Control plots (A. Frumau and H. Vugts,

personal communication, 1998).

Figures 1E and 1F also show that generally the sensible heat flux, ***H***, in the FACE plots was higher (sometimes less negative) than that in the Blower or Control plots as a result of the warmer temperatures in the FACE plots. Comparing figure 1E to 1F, ***H*** in the Low-N plots was higher than that in the High-N plots. One possible reason for this result is that the elevated CO_2 in the FACE plots caused relatively more stomatal closure under Low- compared to High-N, resulting in relatively higher stomatal resistances and canopy temperatures (figure 3A). However, the CO_2- and especially the N-induced changes in crop canopy architecture (Brooks et al., 1997) also might have changed the surface emissivity and the degree of difference between the radiative and aerodynamic surface temperatures (Huband and Monteith, 1986a).

The FACE treatment decreased latent heat flux or evapotranspiration, λET, by an average 6.7% (± 1.2%) for the four seasons under Wet, High-N conditions, as indicated by the slope of the regression line in figures 1C. Under Low-N, the reduction was 19.5% (± 2.5%; Fig. 1D). Regressions for all the individual seasons for the data in figures 1C and 1D (not shown) were in good agreement, which gives confidence in these results.

INTERPRETATION: It appears from these data that irrigation requirements for wheat may be somewhat lower in the future high-CO_2 world (provided that any global warming is small).

FUTURE PLANS: Starting in July 1998, a FACE experiment is underway on sorghum (see Kimball et al., "The Free-Air CO_2 Enrichment (FACE) Project: Progress and Plans," this volume), and micrometeorolgical measurements are being recorded like those in this report for determination of the energy balance components and ***ET***. A second FACE sorghum will be conducted starting in July 1999, and the micrometeorolgical measurements again will be made.

COOPERATORS: See Kimball et al., "The Free-Air CO_2 Enrichment (FACE) Project: Progress and Plans" (this volume).

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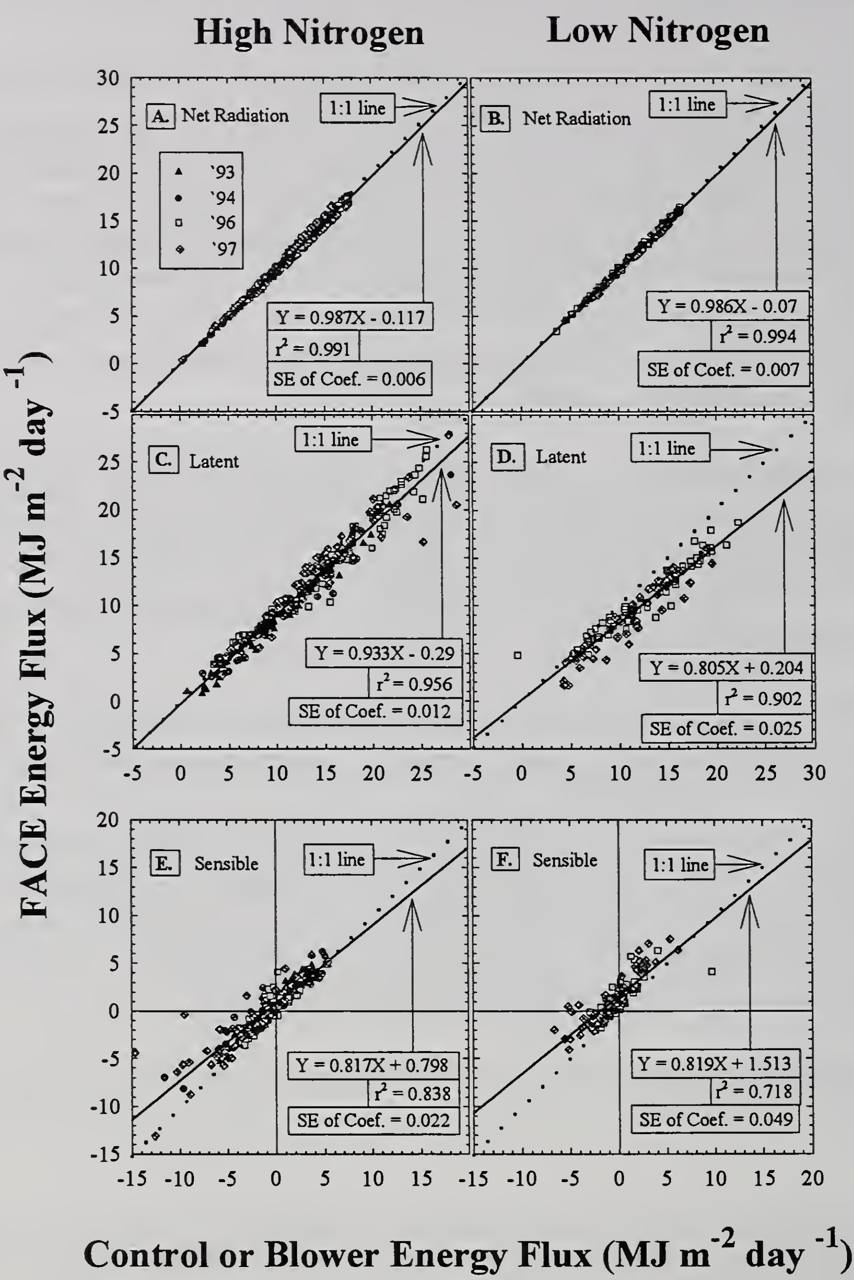

Figure 1. Daily total FACE net radiation, R_n (A and B), sensible heat flux, H (E and F), and latent heat flux, λET (C and D) versus the corresponding Blower or Control values. The left panels (A, C, and E) include data from Wet, High-N plots from all four seasons (1992-3, 1993-4, 1995-6, and 1996-7). The right panels (B, D, and F) include data from Low-N plots from the last two seasons (1995-6 and 1996-7). Each data point from 1992-3 and 1993-4 is an average over dual sets of instruments per plot and over two replicate plots, and each point from 1995-6 and 1996-7 is an average over two replicate plots. About 60 data points per season are plotted about from mid-February until early May (High-N) or late April (Low-N). This selection of data excluded early season data when the instruments viewed soil and late season data when the crop senesced. Also shown are the overall regression lines.

FACE 1998: CHANGES IN PHOTOSYNTHETIC APPARATUS OF SPRING WHEAT IN RESPONSE TO CO2-ENRICHMENT AND NITROGEN STRESS

N. R. Adam, G.W. Wall, B.A. Kimball, P.J. Pinter, Jr. and R.L. LaMorte

BACKGROUND: With the expected doubling of atmospheric levels of CO_2 by sometime in the 21st century, it is important to understand how this change will affect our way of life and, more specifically, how it will affect plant life. Much research has been conducted to determine how plants respond and acclimate to long-term exposure to elevated levels of CO_2 in the field. The Free Atmospheric CO_2 Enrichment (FACE) facility at the University of Arizona Maricopa Agricultural Research Center is helping to address this question. A compilation of the Maricopa FACE data from 1995 and 1996 showed that elevated CO_2 caused final wheat grain yields to rise by an average of 16% under non-limiting water and nutrient conditions (Pinter et al., 1997). However, under lower levels of nitrogen, CO_2 enrichment increased yields by 8%. It is important to investigate whether further increases in atmospheric CO_2 may result in further yield increases. Plants acclimate to changes in CO_2 concentration through changes in the process of photosynthesis. This long-term, acclimation response of photosynthesis can involve regulation of the amount and activity of enzyme required to reestablish a balance within the photosynthetic apparatus. An earlier report (Adam et al., 1997) presented data from a gas-exchange technique in which photosynthesis (A) is measured at a range of intracellular CO_2 concentrations (Ci), providing information on changes within the photosynthetic apparatus. Since Rubisco (the enzyme catalyzing the initial reaction of photosynthesis) capacity is limiting at low values of Ci, the slope of the A-Ci relationship at those low values of Ci can be used to assess changes in the ability of Rubisco to fix CO_2. This slope, called the 'carboxylation efficiency,' can be used as an indicator of down-regulation, in which the amount of Rubisco is decreased in response to the greater concentration of atmospheric CO_2. If down-regulation does occur, we could expect an upper limit to the yield increases commonly seen under CO_2 enrichment. Therefore, the objective of this experiment was to support the carboxylation efficiency data presented by Adam et al. (1997) by assaying the Rubisco activity of the leaves which were used for the A-Ci gas-exchange analysis, and to provide further support for down-regulation.

APPROACH: Hard red spring wheat (Triticum aestivum L. cv. Yecora Rojo) was planted in an open field at the University of Arizona Maricopa Agricultural Research Center, located 50 km south of Phoenix, Arizona (33.1 °N, 112.0 °W). Wheat was sown into flat beds at 0.25-m row spacing on December 15, 1996 at a population of 194 plants m-2, 50% emergence occurred January 1, 1997, and the crop was harvested May 28-29, 1997. Following sowing, a FACE apparatus was erected on site to enrich the CO_2 concentration of the ambient air (ca. 370 mmol mol-1) to ca. 570 mmol mol-1. Nitrogen was applied as a split plot factor using subsurface drip irrigation such that high N plots received 393 kg.ha-1 and the low N plots received 53 kg.ha-1. Beginning with tillering, gas exchange analyses were conducted on the uppermost, fully expanded leaf (referred to as flag leaf), flag minus one and flag minus two. Photosynthesis rates were measured over a range of intracellular CO_2 levels, generating an A-Ci curve. At the end of each curve, the leaf was frozen as quickly as possible with a liquid nitrogen-cooled clamp and stored in liquid nitrogen. Activity of Rubisco was assayed from these leaves. A mixed effects model was used to analyze the data.

FINDINGS: The Rubisco activity data supported the interpretations of the carboxylation efficiency data, indicating that down-regulation of the photosynthetic apparatus in response to elevated CO_2 did occur. Responses of Rubisco activity of wheat to CO_2 enrichment and N fertilization were dependent on growth stage (Figure 1). Strong CO_2 effects were seen for all three leaves of the profile, but the effects were more consistent on the 7th and 6th leaves. The effect of N treatment was most consistent in the flag leaf and the 7th leaf. CO_2 x N interactions were more common in the flag leaf and the 6th leaf. Analyses using protein gels indicated that Rubisco protein content responses to treatment correlated with the carboxylation efficiency and enzyme activity data.

INTERPRETATION: The indications of down-regulation at the gas exchange, enzyme activity and protein content levels in wheat provide strong evidence that there is an upper limit on the yield increases of cool-season crops such as wheat that have been measured under higher atmospheric CO_2 concentrations. It also suggests that the response is dependent on growth stage as well as on the position of the leaf within the canopy.

FUTURE PLANS: A manuscript is being prepared. Elemental analyses may be conducted to determine the extent of N stress associated with each treatment. Gas exchange measurements have also been conducted on sorghum (See Kimball et al., The Free-Air CO_2 Enrichment Project: Progress and Plans, this volume) to determine whether CO_2 enrichment causes similar responses in warm-season crops. Further analysis of the sorghum gas exchange data as well as the supporting biochemical assays will be conducted.

COOPERATORS: We wish to acknowledge the collaborative efforts of Andrew Webber of Arizona State University for helpful advice and the use of his laboratory; Steve Leavitt, Alan Matthias, and Tom Thompson of the University of Arizona; Bob Roth, Pat Murphree and Roy Rauschkolb from the Maricopa Agricultural Center; Keith Lewin, John Nagy and George Hendrey of Brookhaven National Laboratory; and Frank and Gabrielle Wechsung and Thomas Kartschall from the Potsdam Institute for Climate Research. We also thank Jose Olivieri for technical assistance.

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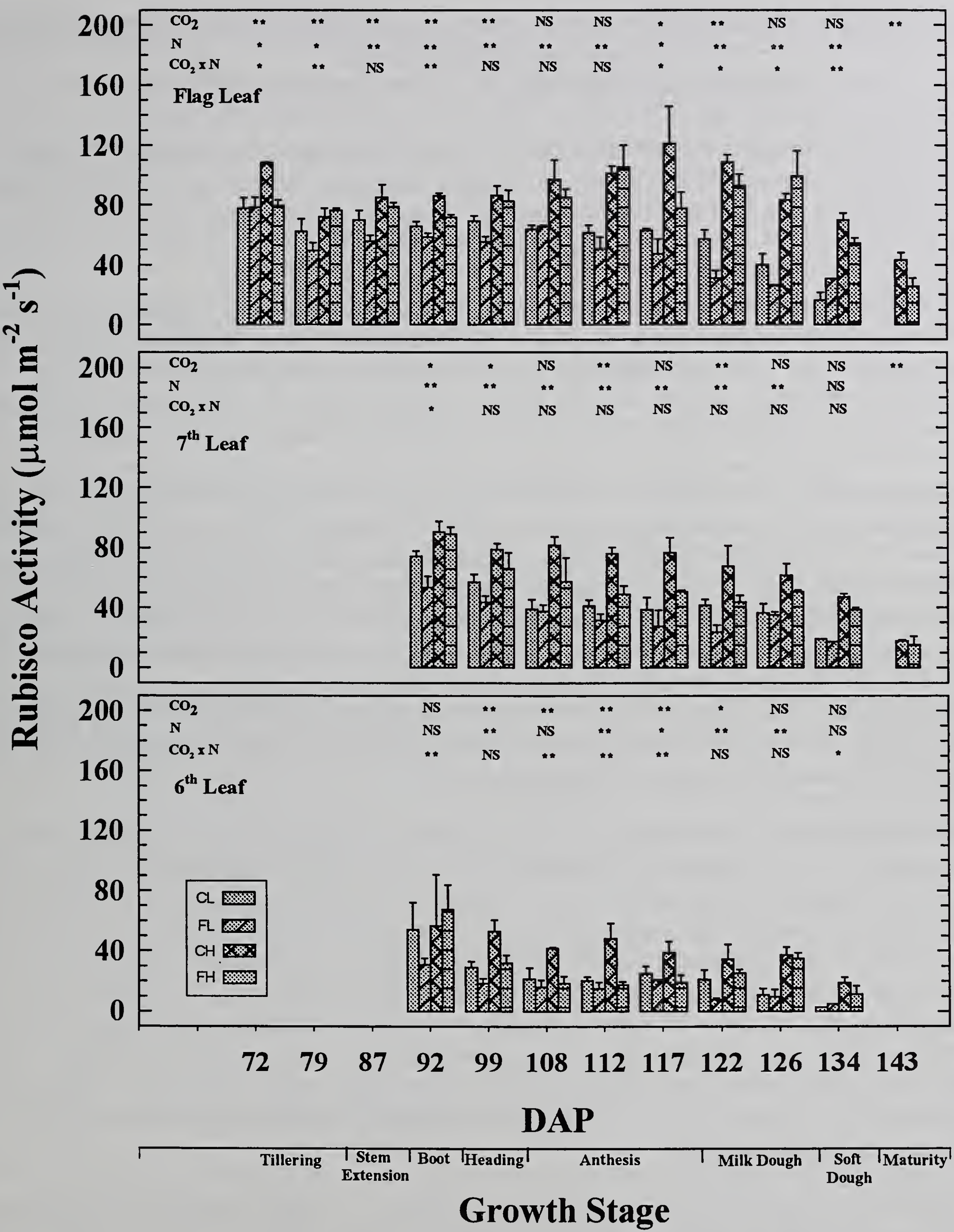

Figure 1. Activity of fully activated Rubisco for flag leaf (uppermost, fully-expanded leaf), 7th leaf and 6th leaf of wheat throughout the season by DAP (Days after Planting). One asterisk indicates significance at α=0.2 and two asterisks indicate significance at α=0.1.

EFFECTS OF WATER STRESS AND CO_2 ON SORGHUM CANOPY ARCHITECTURE AND GAS EXCHANGE: A RATIONALE FOR STUDY AND PROGRESS REPORT

T.J. Brooks, Research Technician; G.W. Wall, Plant Physiologist; P.J. Pinter, Jr., Research Biologist; B.A. Kimball, Soil Scientist; J.M. Triggs, Biological Science Aid; N.R. Adam, Plant Physiologist; R.L. LaMorte, Civil Engineer; F.J. Adamsen, Soil Scientist; and D.J. Hunsaker Agricultural Engineer

PROBLEM: Until 1966 it was widely thought that all photosynthetic organisms fixed carbon dioxide (CO_2) by carboxylating ribulose-1,5-bisphosphate, using ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), to form two molecules of 3-phosphoglycerate (3-PGA). This process was named the C_3 photosynthetic pathway. While working at a sugar refinery in Australia, Marshall Hatch and Roger Slack discovered that the primary initial products of photosynthesis in sugar cane were malate and aspartate, not 3-PGA (Hatch, 1992). The primary carboxylating enzyme associated with this process was discovered to be phosphoenolpyruvate carboxylase (PEPC). This "new" photosynthetic process was quickly named the C_4 pathway. Within ten years a temporally shifted version of the C_4 photosynthetic pathway, crassulacean acid metabolism (CAM), was resolved. Though variations occur, it has been determined that all higher plants assimilate CO_2 or HCO_3^- as a source of carbon through one of these three major pathways: C_3, C_4, and CAM. Both C_4 and CAM carbon assimilation pathways utilize physiological and morphological adaptations to concentrate CO_2 within the leaf. The discovery of CO_2 concentrating mechanisms has lead to the belief that C_4 and CAM evolved in response to a prehistoric decline in atmospheric CO_2 concentration. It is estimated that atmospheric CO_2 fell from 3,000 μmol mol^{-1} during the late Cretaceous Period to 350 μmol mol^{-1} during the Miocene Epoch, some 24 million years ago.

All three photosynthetic pathways are found in modern day horticulture and agriculture. The vast majority (93%) of the approximately 250,000 - 275,000 species of angiosperms utilize the C_3 photosynthetic pathway and are present in every order. C_3 plants are present on every continent and representative samples may be found in every major body of water. The majority of all agriculturally important crops are C_3 and include wheat, barley, rice, cotton, and mungbean. Though such a large number of species represents an almost infinite diversity, some basic anatomical characteristics remain constant throughout. Leaf bundles are composed of parenchymatic tissue. The air space volume of C_3 monocotyledons is reported to be between 10 and 35% of the total leaf volume. In C_3 dicotyledons, the leaf is a bit more vacuous, where the air space ranges from 20-55%. The average cell diameter for C_3 plants is 20 μm. All species contain stomates, with some species hemistomatal while others are amphistomatal.

The primary carboxylating enzyme for carbon assimilation in C_3 plants is Rubisco, though PEPC is present (approximately 20:1 ratio of Rubisco to PEPC). Rubisco may account for as much as 50% of all soluble leaf protein. Total leaf nitrogen content ranges from 200 to 260 mmol m^{-2} (leaf area). To fix one mole of CO_2, 3 moles of ATP and 2 moles of NADPH are required. The range of ^{13}C content in C_3 tissues is -40 to -15‰ (average -23‰).

The highest known photosynthesis rate for a C_3 species (*Camissonia claviformis*) is reported to be 59 µmol m^{-2} s^{-1} (Ehleringer et al, 1979), though typical maximum rates range from 10 to 40 µmol m^{-2} s^{-1} at an optimal temperature between 15 and 25 °C. Light saturation level for C_3 photosynthesis occurs at approximately 1200 µmol photons m^{-2} s^{-1} (400-700 nm photosynthetically active radiation, PAR). Photorespiration may be as great as 50% of the gross photosynthesis rate and C_i/C_a may range from 0.30 to 0.85.

It has been estimated that there are only 1,000 species of C_4 plants (Hopkins, 1995); 2000 may be a more likely number. C_4 physiology is represented in 15 dicot and 3 monocot families (Hopkins, 1995). No single plant family is exclusively C_4, and species have not been reported in Bryophta, Pterophtya or Conifierophyta. Though C_4 plants live in a wide variety of habitats, ranging from aquatic environments (Nelson and Langedale, 1992) to shade adapted trees (Piercy and Ehleringer, 1984) to woody shrubs in the cold Eurasian desert (Winter, 1981), most occupy warm dry environments. C_4 examples in agriculture include sugar cane, corn, and sorghum.

The exterior appearance of a C_4 plants is indistinguishable from that of a C_3. The most readily identifiable characteristic of a C_4 plant are the chlorenchymatic bundle sheath cells surrounding leaf vascular elements. This arrangement is called Kranz anatomy (literally translated from German, wreath). Leaf tissue tends to be more "dense" then those of C_3 plants: the air space for C_4 monocots is less than 10% of the total cell volume, for C_4 dicots, less than 30%. Like C_3 plants, the average cell size is approximately 20 µm.

The C_4 carbon assimilation pathway has three basic types: the NADP - Malic enzyme type (sorghum), the NAD - Malic enzyme type, and the Phosphoenolpyruvate carboxykinase type. PEPC is the primary carboxylating enzyme for all three types. Energetically, for each CO_2 fixed, five ATP and 2 NADPH are required. Krantz anatomy compartmentalizes the carbon assimilation pathway into the bundle sheath cells and the mesophyll, resulting in the compartmentalization of PEPC and Rubisco (overall ratio of concentration is 4:1). As such, the isotopic ^{13}C content of C_4 leaf tissue is less negative than that of a C_3, ranging from -10 to -18‰ (average -14‰). Compartmentalization and PEPC act to serve as a CO_2 concentrating mechanism and thus reduce respiratory CO_2 loss to less than 1% of the net assimilation rate. The resulting CO_2 compensation point is between 0 and 10 µmol mol^{-1} CO_2. The maximum reported photosynthesis rate for a C_4 plant occurs in *amaranthus palmerii*, which was reported at 81 µmol m^{-2} s^{-1} (Ehleringer, 1983). Stomatal conductance rates are typically between 8 and 12 mm s^{-1} at midday. Leaf nitrogen content in C_4 plants ranges from 120-180 mmol m^{-2} leaf area. The maximum rate of photosynthesis occurs at approximately 1600 - 1800 µmol photons m^{-2} s^{-1} (PAR) and at a temperature range of 30 - 45 °C.

A plant is generally considered to use C_4-type photosynthesis when the following conditions are met (from Edwards and Walker, 1983):

1. Primary initial products of photosynthesis are the C_4 dicarboxylic acids oxaloacetate, malate, and aspartate.
2. Carbon is donated from the C_4 acids into the RPP pathway of photosynthesis.

3. These events occur in the light.
4. There are two photosynthetic cell types, mesophyll and Kranz (bundle sheath) cells.

The Intergovernmental Panel on Climate Change (IPCC) reports that global CO_2 levels will rise from the current ambient level of 370 μmol mol $^{-1}$ to over 500 μmol mol $^{-1}$ by the end of the 21 st century (IPCC, 1995). Of primary concern to the human population is the impact that rising global CO_2 concentrations will have on agriculture. The USWCL Environmental and Plant Dynamics (EPD) group has been investigating the impact of increased CO_2 and water stress on various C_3 agricultural crops for the past 8 years through the use of a Free-Air CO_2 Enrichment apparatus (FACE) (Hendrey, 1993; Hendrey and Kimball, 1994). Previous FACE experiments used small ($1m^2$) pop-on chambers to measure the rates of net photosynthesis and canopy conductance, thereby providing "snapshots" of crop physiology. Results from these investigations have enabled members of the EPD group to conclude that canopy photosynthesis and water use efficiency are improved in C_3 plants, such as wheat and cotton, when subjected to CO_2 enriched environments (Kimball *et al.,* 1995).

The FACE 1998-9 investigation seeks to understand if improved plant growth and yield will hold true when sorghum, a C_4 plant, is grown for a CO_2-enriched x water stress experiment. Though an increase in whole-canopy photosynthesis is not expected for true C_4 photosynthesis, some enhancement may occur through C_3 photosynthesis which is present during organ development. If the C_3 contribution responds dramatically to CO_2 enrichment, as could be the case during vegetative growth, the additional biomass gained may sufficiently alter the canopy light environment. As was demonstrated in the FACE wheat experiments, the alteration of canopy light environment in effect creates a third treatment which spurs modification of canopy architecture. In turn, modification of canopy architecture acts as a compensation mechanism which may limit observable treatment effects.

APPROACH: Four 25-m-diameter rings were placed in the field and used continually to enrich the CO_2 concentration of the air to 200 μmol mol $^{-1}$ above ambient. Four identical rings served as controls. Ample water was applied to one half of each ring, while the other half was subjected to water stress (strip-split plot design). "Flow-through" chambers (Brooks *et al.*, 1999) were placed in treatment replicates 3 and 4 and were used to collect canopy carbon exchange data for a period of 10 days. At the end of this time period the chambers were moved to a new location within the treatment. Measurements of canopy greenness, plant area index (PAI), mean leaf tip angle distribution (LTA), and solar radiation (PAR) were made on a weekly basis. Resulting data are in the process of being analyzed.

FINDINGS: As of the writing of this report, data collection and analysis were still under way. Initial analysis appears to confirm that photosynthesis was enhanced by CO_2 enrichment during vegetative growth. Water stress and CO_2 enrichment did cause the onset of four distinct canopy architectures. CO_2 enriched, amply-watered plots gained the most biomass, whereas ambient-CO_2, water-stressed plots appeared to have gained the least.

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CO_2 ENRICHMENT OF TREES

S.B. Idso, Research Physicist; and B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The continuing rise in the CO_2 content of Earth's atmosphere is believed by many people to be the most significant ecological problem ever faced by humanity, primarily because of the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. There are also, however, many *beneficial* effects of elevated atmospheric CO_2 concentrations that are experienced by Earth's plant life; and some of them, such as the ability of elevated CO_2 to enhance plant growth rates, actually impact the global warming problem. Earth's trees, for example, account for two-thirds of the planet's photosynthesis and are the primary players in the global cycling of carbon, removing CO_2 from the air and sequestering its carbon in their tissues and, ultimately, the soil. Consequently, we seek to determine the direct effects of atmospheric CO_2 enrichment on the growth and development of trees, concentrating specifically on the long-term aspects of this phenomenon; for until someone conducts an experiment that is measured in *decades*, we will never know what the long-term impact of the ongoing rise in the air's CO_2 content will be on the planet's most powerful contemporary carbon sink.

APPROACH: In July 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. CO_2 enrichment—to 300 ppmv (parts per million by volume) above ambient—was begun in November 1987 in two of these chambers and has continued unabated since that time. Except for this differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated and fertilized as deemed appropriate for normal growth (Idso and Kimball, 1997).

As in all prior years, we continue to measure the circumferences of the trunks of the trees at the midpoint of each month; and from these data we calculate – on the basis of relationships developed specifically for our trees (Idso and Kimball, 1992) – monthly values of total trunk plus branch volume. Then, from wood density (dry mass per fresh volume) measurements we have made over the past several years, we calculate monthly values of the total dry weight of the trunk and branch tissue of each tree. Results for December, January, February and March – the winter period of virtually no trunk expansion – are then averaged to give a mean value for the year, from which the preceding year's mean value is subtracted to yield the current year's production of trunk and branch biomass.

We likewise continue our yearly fruit measurements, which consist of counting the number of fruit to reach maturity on each tree, weighing each such fruit individually, and determining the percent dry weight of one hundred ripe fruit from each tree, which allows us to calculate the total dry weight of fruit produced in each of the CO_2 treatments.

The last major component of aboveground biomass that we regularly assess is leaf tissue. From previously derived relationships (Idso and Kimball, 1992), we evaluate the number of new leaves produced each year from our trunk circumference measurements. And from bimonthly assessments

of leaf dry weight similar to those of Idso et al. (1993), we calculate the total dry weight of leaves produced on the trees each year. These results, added to the trunk and branch dry weights and fruit dry weights, then give us the total aboveground dry weight production per year for all of the trees in the two CO_2 treatments.

Results for this past year – which marks the completion of the first *decade* of this study – continue to be encouraging. They indicate that the trees of both CO_2 treatments may have reached a condition of maturity characterized by a near-steady-state of yearly aboveground biomass production (see Figure 1). After increasing monotonically over the first eight years of the experiment, the value of this parameter in the CO_2-enriched trees for years 8, 9 and 10 was 107, 90 and 95 kg/tree, respectively; while for the ambient-treatment trees it was 62, 51 and 57 kg/tree, producing a three-year-mean CO_2-enriched/ambient-treatment ratio of 1.72.

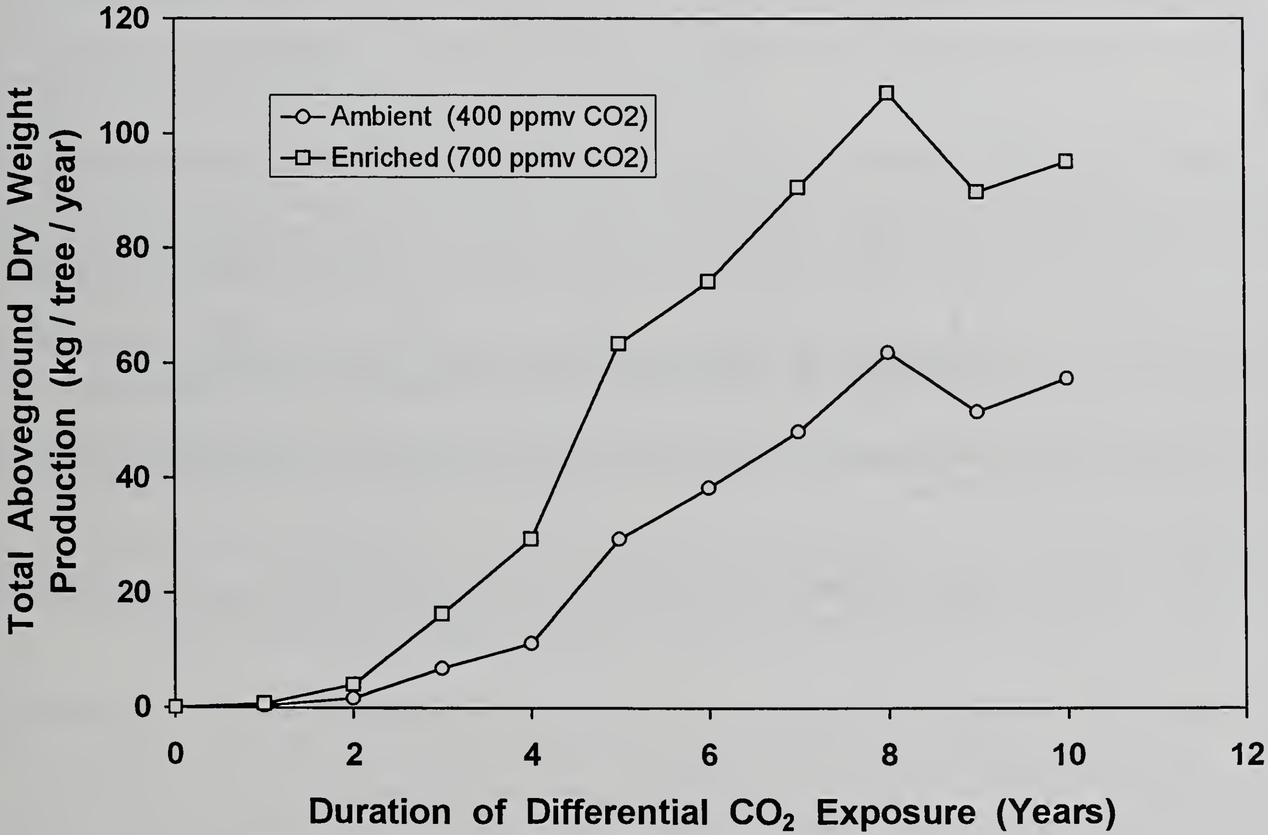

Figure 1. Yearly total aboveground biomass production in the ambient and CO_2-enriched sour orange trees as a function of time since the start of the experiment.

Fruit production has also been fairly steady in both sets of trees for the last four years (see Fig. 2). For years 7, 8, 9 and 10 it has been 39, 47, 38 and 38 kg/tree in the CO_2-enriched trees, respectively; while in the ambient-treatment trees it has been 18, 25, 13 and 23 kg/tree, producing a four-year-mean CO_2-enriched/ambient-treatment ratio of 2.05. However, the year to year variability in fruit

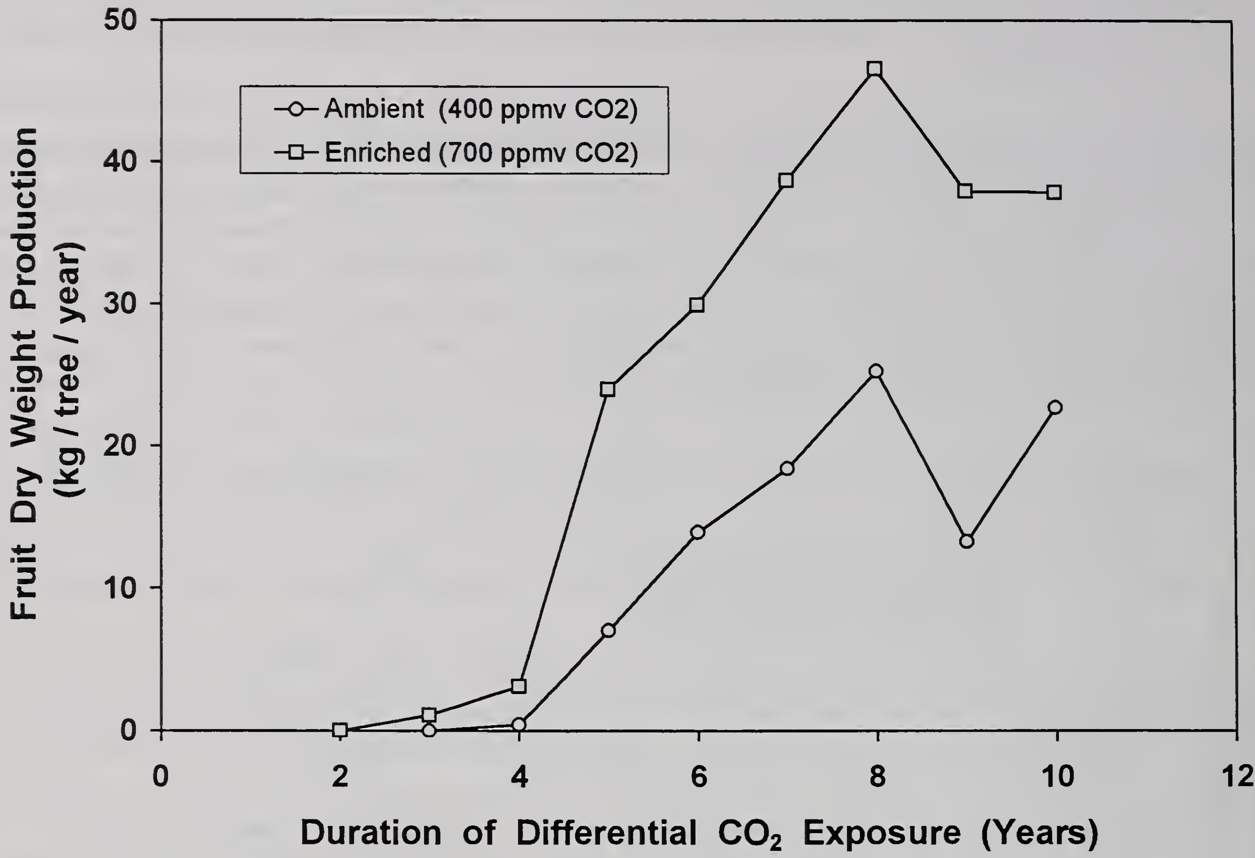

Figure 2. Yearly fruit dry weight production in the ambient and CO_2-enriched sour orange trees as a function of time since the start of the experiment.

production is still too great confidently to resolve the issue of the trees' long-term equilibrium response to atmospheric CO_2 enrichment without acquiring several more years of data.

What happens from this point of the study could be of greater significance than all that has preceded it, for we are now in a position to broach the question of the asymptotic *equilibrium* response of the trees to atmospheric CO_2 enrichment. We should soon know, for example, if there even is such a thing as a long-term equilibrium response, where each succeeding year sees the yearly biomass production of the trees in each treatment fluctuate about two different but near-constant means. If such is the case, and it remains so for a significant span of years, the implication would be that the extra 300 ppmv of atmospheric CO_2 in the CO_2-enriched tree enclosures would *always*-- from the point of inception of the two plateaus -- produce about the same percentage biomass enhancement, which for our study would appear (so far) to be approximately 72%. The alternative is for the yearly percentage biomass enhancement to continue the gradual slow decline it exhibited between years 2 and 8 of our study, dropping to (a) some much lower positive value, (b) zero, or (c) a negative value.

INTERPRETATION: The stakes in this study are high, as no one has ever maintained an experiment such as ours for a long enough time to determine the long-term consequences of atmospheric CO_2 enrichment for long-lived woody plants. Indeed, the answer to this question is one of the critical elements that is needed to reveal the ultimate fate of the CO_2 that the people of the world yearly emit to the atmosphere. Will the trees of the planet be sufficiently stimulated by the ongoing rise in the air's CO_2 content to remove enough of it from the atmosphere to prevent a significant CO_2-induced warming of the globe? Our study provides important insight into this question and may help our government and others craft appropriate policies to meet this global environmental challenge. In the meantime, our findings continue to demonstrate that carbon dioxide is an effective aerial fertilizer, significantly increasing the size, growth rate, and fruit production of one- to ten-year-old sour orange trees exposed to 75% more CO_2 than is normally in the air.

FUTURE PLANS: We hope to continue the sour orange tree experiment for as long as it takes to determine whether or not the trees will truly achieve steady-state yearly growth rates that produce a CO_2-induced productivity enhancement that can reasonably be expected to remain essentially constant over the remaining years of the trees' life span.

COOPERATORS: *Institutions:* Arizona State University, Departments of Botany and Geography; Center for the Study of Carbon Dioxide and Global Change; Institute for Biospheric Research; U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research. *Personnel:* R.C. Balling, Jr., J.K. Hoober, C.E. Idso, K.E. Idso, J. LaRoche, S.P. Long, H.-S. Park

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SIMPLE TECHNIQUES FOR CONDUCTING CO_2 ENRICHMENT AND DEPLETION EXPERIMENTS ON AQUATIC AND TERRESTRIAL PLANTS: THE "POOR MAN'S BIOSPHERE"

S.B. Idso, Research Physicist

PROBLEM: In order to act in the best interests of the biosphere in the face of the rising CO_2 content of earth's atmosphere, we need to determine the effects of atmospheric CO_2 enrichment on the growth habits of as many different plants as possible, both singly and in combination with competing plants and animals. Also needed is a knowledge of how the ongoing rise in the air's CO_2 content may interact with environmental changes such as global warming, more frequent and intense drought, and intensified soil, water, and air pollution, so that we can determine whether the deleterious effects of these latter phenomena will be ameliorated or exacerbated by the concurrent rise in atmospheric CO_2. Consequently, in an attempt to expand our research capabilities in this important area of science and to interest more young people in pursuing careers therein, this project has as its goal the development of a number of simple and inexpensive experimental techniques that will enable almost anyone to conduct significant research on a variety of questions related to the role of atmospheric CO_2 variability in ongoing and predicted global environmental change.

APPROACH: Over the first three years of the project, a set of guidelines was developed for using inexpensive and readily available materials to construct experimental growth chambers or "Poor Man's Biospheres," wherein CO_2 enrichment and depletion studies of both aquatic and terrestrial plants could be conducted. In their most basic form, these enclosures consist of no more than simple aquariums covered by thin sheets of clear polyethylene that are taped to their upper edges to isolate their internal air spaces from the room or outside air. Several low-cost, low-technology ways of creating a wide range of atmospheric CO_2 concentrations within these enclosures were also developed. Some of the CO_2 enrichment techniques utilize the CO_2 that is continuously evolved by the oxidation of organic matter found in common commercial potting soils, while others rely on the CO_2 that is exhaled by the experimenter. When CO_2 depletion is desired, the growth of the experimental plants themselves can be relied upon to lower the CO_2 contents of the biospheres' internal atmospheres, as can the photosynthetic activity of ancillary algal populations that often occur in watery habitats and that can be induced to grow in terrestrial environments as well. For all of these different situations, a set of simple procedures for measuring biospheric airspace CO_2 concentration has been developed. This technique utilizes any of a number of simple colorimetric CO_2 test kits that are sold in tropical fish stores throughout the world and that can be readily obtained by ordering over the internet (Idso, 1997).

To obtain hands-on experience in the technology transfer aspect of the Poor Man's Biosphere Program, outreach activities were initiated two years ago with five eighth-grade biology classes at McKemy Middle School in Tempe, Arizona, and with a fifth-grade class at the Salt River Elementary School of the Salt River Pima-Maricopa Indian Community. Students at both schools investigated the effects of atmospheric CO_2 enrichment and depletion on a common terrestrial plant, Devil's Ivy or Golden Pothos (*Scindapsus aureus*), and a common emergent aquatic plant, Yellow Water Weed

(*Ludwigia peltoides*), under two different light intensities. New sets of students at McKemy Middle School repeated the Pothos experiment last year with some slight variations. Also, two honors biology classes at Tempe High School conducted a massive twice-replicated study of the growth response of a submerged aquatic macrophyte, Corkscrew Vallisneria (*Vallisneria tortifolia*), to three levels of atmospheric CO_2 (ambient, half-ambient, and twice-ambient) at three different water temperatures and two different light intensities, winning a $10,000 first-place award in a state environmental science curriculum contest.

Work continues this year at both McKemy Middle School and Tempe High School. In addition, as part of its environmental science education activities, the Center for the Study of Carbon Dioxide and Global Change has begun an ambitious program of employing the poor man's biosphere technique in a set of experiments that it describes on its website (www.co2science.org) and updates on a weekly basis. By means of a special presentation to members of the Arizona Science Teachers Association at its most recent annual meeting, this program was brought to the attention of several teachers at both the junior and senior high school levels in an attempt further to expand its usage in a wide-ranging test that is based solely on internet communication.

FINDINGS: The simple experimental techniques developed in the initial years of the program have been found to work satisfactorily in actual classroom environments at elementary, middle and high school levels.

INTERPRETATION: As the technology transfer aspects of the program are still ongoing, final conclusions have not yet been reached. However, all indications are that the poor man's biosphere approach to atmospheric CO_2 enrichment and depletion experiments has the potential to become a key element of environmental science education curricula in the years ahead.

FUTURE PLANS: Outreach activities will continue for at least one more year at all of the currently cooperating schools, after which one or more journal articles devoted to teaching the Poor Man's Biosphere Program will be prepared. Efforts to bring the program to state and national audiences of science teachers will continue via the internet in cooperation with educational organizations that have the capacity to provide such services.

COOPERATORS: Center for the Study of Carbon Dioxide and Global Change (C.D Idso, K.E. Idso); McKemy Middle School, Tempe Elementary School District (M. Davis); Salt River Elementary School, Salt River Pima-Maricopa Indian Community (K.E. Idso); Tempe High School, Tempe Union High School District (S. Greenhaulgh).

REFERENCE: Idso, S.B. 1997. The poor man's biosphere, including simple techniques for conducting CO_2 enrichment and depletion experiments on aquatic and terrestrial plants. *Environmental and Experimental Botany* 38: 15-38.

OZONE OBSERVATIONS FROM MARICOPA AND CASA GRANDE, ARIZONA, TAKEN DURING THE 1993-1997 FREE-AIR CO_2 ENRICHMENT (FACE) WHEAT EXPERIMENTS

B.A. Kimball, Soil Scientist

PROBLEM: Elevated CO_2 causes partial stomatal closure, as reported in the literature (e.g., Morison, 1987) and as evidenced by decreased stomatal conductance in the free-air CO_2 enrichment (FACE) wheat experiments (e.g., Garcia et al., 1998) conducted at the University of Arizona Maricopa Agricultural Center (MAC), Maricopa, Arizona. Such stomatal closure could afford some protection from ozone (O_3), which could result in better growth of the plants and which would masquerade as a CO_2-stimulation growth response rather than an ozone protection response. Therefore, it was decided to monitor O_3 over the wheat crop during the 1996-7 FACE Wheat Experiment in order to have some basis for determining whether ozone levels were high enough to be of concern in the interpretation of the results from our experiments. This report presents a summary of these O_3 observations from the wheat field at MAC as well as from the nearby Casa Grande Airport, Casa Grande, AZ.

APPROACH: References to the methodologies of the FACE Wheat experiments are given by Kimball et al. and others in this volume. To measure O_3, an analyzer was housed in an air-conditioned shelter at the south edge of the field. A 15-m-long teflon sampling tube was passed out of the shelter and extended about 3 m into the field. A funnel was inserted into the end of the tube and mounted (inverted) about 0.2 m above the top of the wheat canopy. The O_3 observations commenced on March 6, 1997, and continued until the end of May. Hourly average O_3 concentrations were recorded. The instrument was serviced weekly, which consisted of raising the inlet funnel to maintain the height above the canopy and checking a filter that was positioned at the end of the sampling tube just at the inlet to the analyzer. The filter was changed at 2-3 week intervals. At the end of the growing season, the O_3 analyzer was removed from the field and taken to the Department of Environmental Services, Maricopa County, Phoenix, Arizona, for calibration. It was cross-calibrated against an EPA-certified instrument using concentrations of 0, 90, and 400 ppb from an O_3 generator. The procedure revealed that the instrument was reading low by about 22% and 10% with and without the long sampling tube, respectively. Therefore, the data from the field were adjusted upward using the calibration factor obtained when the sampling tube was in place. This adjustment may be too high for early in the season because possibly the tube became progressively dirty during the course of the season and may not have caused the instrument to read quite as low at the beginning of the season as it did at the end.

Ozone data from 1993 through 1997 were also obtained from the Pinal County Air Quality Control District, Florence, Arizona, specifically the observations from the Casa Grande Airport, which is about 16 miles southeast of the MAC field site. Like MAC, the Casa Grande Airport site is mostly rural, but the town of Casa Grande is about 3 miles south of it. Regressions were run between the MAC and the 1997 Casa Grande data for all the hours that both sites had valid data. Then, the regression equation was used to estimate MAC data from emergence until March 6th and for a few other small gaps in the data caused by recorder problems.

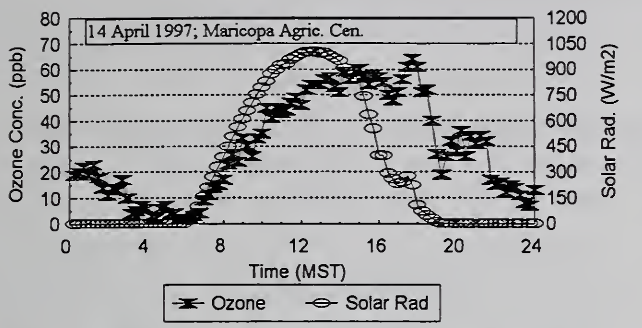

Figure 1. Diurnal pattern of O_3 and solar radiation at Maricopa Agricultural Center on April 14, 1997, a typical day.

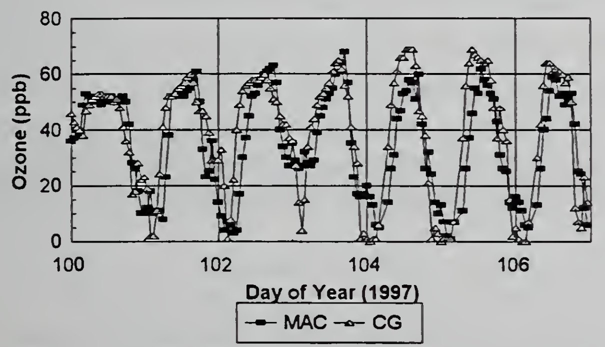

Figure 2. Comparison of the O_3 concentraions observed at the Maricopa Agricultural Center (MAC) and the Casa Grande Airport (CG) from Day-of-Year 100-107 (10-17 April) 1997.

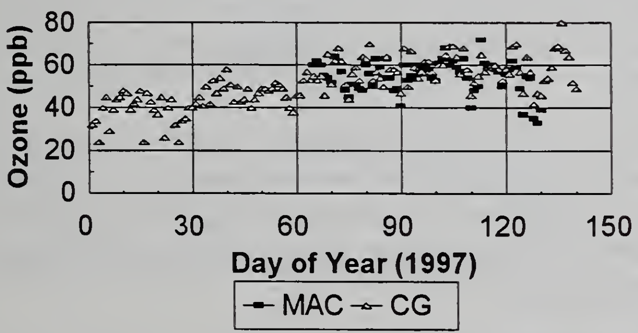

Figure 3. Daily maximum O_3 values observed at MAC and CG during the 1997 wheat growing season.

FINDINGS: A fairly typical pattern of O_3 concentration is shown figure 1 for April 14, 1997. Starting from low (10 ppb) levels at dawn, it increased during the day to reach a peak near mid-afternoon, followed by a decline at night. A comparison between the MAC and Casa Grande Airport data is presented in figure 2 for the week of April 10-17 (DOY 100-107), and the daily maximums are shown for the whole season in figure 3. There were no "episodes" of really high concentrations as sometimes reported near urban areas. The agreement appears to be fairly close between the data for these two sites. The MAC data appear to lag those from Casa Grande somewhat, particularly in the mornings (figure 2). The Casa Grande site appears to experience higher afternoon peaks and lower predawn minimums than observed at MAC, which is reflected in the regression equation (figure 4) of the MAC data on the Casa Grande data.

Several O_3 exposure indices were calculated. Accumulated exposures Over Thresholds of 0, 10, 40, and 60 ppb were calculated as the sums of the 1-hr mean O_3 concentrations that were greater than the particular threshold during daylight hours. The MAC values from emergence until 75% senescence (the latter being defined as the day of the year when only 25% of the leaf biomass remained green in the ambient CO_2 plots that received ample water and nitrogen, Paul Pinter, Jr., personal communication) amounted to 60,800; 43,712; 5,913; and 54 ppb-hr for AOT0, AOT10, AOT40 and AOT60, respectively. For the 3-month February-April period, the values were 44,800; 33,330; 5,455; and 51; from flowering through milky ripe stage they were 8,792; 6,709; 1,293; and 4 ppb-hr. The season-long mean O_3 concentration was 40.5 ppm at MAC. Corresponding values for Casa Grande were 50.0, 42.5, 47.7, and 44.5 ppb for 1993, 1994, 1996, and 1997.

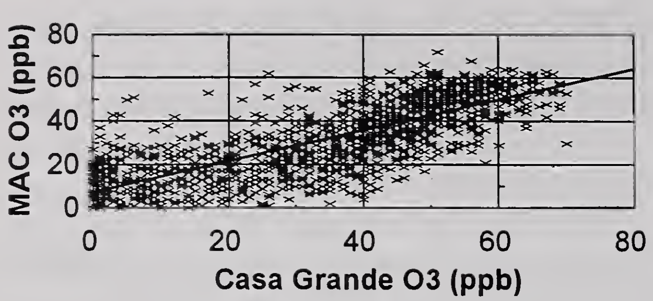

Figure 4. Comparison of the O_3 concentrations observed at MAC versus those observed at CG from DOY 65-130, 1997. The regression equation is Y=0.710X + 7.65 (r^2=0.635; S.E. of coefficient = 0.014).

INTERPRETATION: Interpretation of these data is difficult because of the large variation in the results from the several reports that relate ozone exposure indices to spring wheat response. Using the observed 1997 O_3 indices for MAC, the relative yields for MAC compared to those obtainable in ozone-free air are the following based on the reports of several investigators: 90% or 99% [Fehrer (1993)], 83% or 92% [Ojanperä et al. (1998)], 88% [Pleijel et al. (1995)], 98% or 77% [McKee et al. (1997)], 70% [Unsworth and Geissler (1992)], 94% [Hogsett et al. (1992)], 99% [Miller (1992)], and 92% [Skärby et al. (1992)]. Thus, the wheat yields from well-irrigated, ambient-CO_2 fields may or may not have been significantly reduced by O_3, depending upon which experiment in the literature one chooses to believe. If the AOT40 or AOT60 indices are taken as more indicative of likely plant damage, then the relative yields for MAC ranged from 90 to 99% with a mean of about 95%, i.e., wheat yields at MAC were probably reduced about 5% in 1997 because of ozone pollution.

These relative yield values are for the ambient CO_2, well-watered condition. The FACE treatment reduced stomatal conductance by about 36% at midday (Garcia et al., 1998), which would reduce O_3 exposure by a similar amount, assuming for a first approximation that exposure is proportional to stomatal conductance. Thus, the FACE treatment likely provided about a 2% (36% of 5%) increase in relative yield because of protection from O_3 exposure, which was confounded within the observed 16% increase (Pinter et al., 1997) attributed to the direct stimulation of photosynthesis and growth by the elevated CO_2. Of course, this could have been as much as 12% or less than 1% if the one of the extreme ends of the range of relative yield reported in the literature is correct.

FUTURE PLANS: Monitoring of O_3 levels during the FACE sorghum experiments will be continued (see Kimball et al. "The Free-Air CO_2 Enrichment (FACE) Project: Progress and Plans," this volume) and to characterize the O_3 concentrations within the sour orange tree chambers (see Idso and Kimball, "CO_2 enrichment of trees," this volume). The feasibility of having cooperators conduct controlled ozone exposure experiments will also be explored.

COOPERATORS: Maurizio Badiani, Universitá della Tuscia, Viterbo, Italy; L.G. Mace and S. Belone, Maricopa County Environmental Services Department, Phoenix, AZ; Joseph E. Miller, USDA-ARS, Air Quality Research Unit, Raleigh, NC; Michael Sundblom, Pinal County Air Quality Control District, Florence, Arizona

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EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) AND SOIL WATER AND SOIL NITROGEN ON THE ROOT GROWTH OF SPRING WHEAT

G.Wechsung, Soil Scientist; G.W. Wall, Plant Physiologist; F. Wechsung, Crop Scientist; B.A. Kimball, Supervisory Soil Scientist; P.J. Pinter, Jr., Research Biologist; F.J. Adamsen, Soil Chemist; D.J. Hunsacker, Agricultural Engineer; R.L. La Morte, Civil Engineer

PROBLEM: As carbon dioxide (CO_2) in the atmosphere increases, alterations of terrestrial ecosystems may occur. Critical to the understanding of the consequences of global climate change for terrestrial ecosystems is the role of the root system and below-ground processes in regulating plant responses to rising CO_2. A larger root system growing in high CO_2 would be an important sink for increasing fixed carbon in CO_2-enriched agricultural and natural ecosystems. Therefore one important objective of the Free-Air CO_2 Enrichment (FACE) Wheat Project was to evaluate the effects of CO_2 on wheat root growth.

APPROACH: Spring wheat (*Triticum aestivum* L. cv Yecora Rojo) was grown at The University of Arizona Maricopa Agricultural Center (MAC) for four years under elevated CO_2 using the FACE facility: FACE (~200 µmol mol^{-1} above ambient air) and Control (~370 µmol mol^{-1}) main plot. During the first two years (1992-93&1993-94), differential irrigation was supplied. One half of each main plot was irrigated at a target rate based on 100% replacement of potential evapotranspiration (Wet), and the other half was irrigated at a target rate of 50% (Dry). In the third and fourth years (1995-96&1996-97) full irrigation of 100% evaporate demand was applied, but CO_2 treatments were split to test different nitrogen fertilization regimes (High N ~350 kg N ha^{-1}, and Low N <75 kg N ha^{-1}).

Root core samples were taken during the growing season when the crop reached three-leaf stage, tillering, stem elongation, anthesis, milk development, dough development and post harvest. Root cores (86 mm ID) were collected from two sample positions (in row and inter row) using a gas-driven soil core device. Extracted cores were divided into individual core sections from the top of the soil profile downwards in 0.15 m steps to 0.6 m soil depth, and in 0.2 m sections from 0.6 to 1-m depth. Root and organic debris material were elutriated from the soil with a hydropneumatic elutriation system. Live (intact, white-coloured) roots were separated manually, oven dried for two days at 86 °C, desiccator cooled, and weighed. During milk development, dough development and post harvest in the FACE x Nitrogen project, dead roots (brown coloured) were also extracted. Root length and surface area for the entire core volume were determined using a camera-imaging system. Derived root parameters like root mass density, diameter, and volume were computed from root dry mass, length and area.

FINDINGS: In all four growing seasons, [CO_2] enrichment stimulated root growth during the entire season at different depths of the 1-m soil profile and in the horizontal direction with the consequence of a more developed, more branched root system indicated by the measured parameters root biomass, length, and area. Averaging the root mass over the period between tillering and post harvest for both years of the FACE x Water experiment (1992-93&1993-94), increases of 26% increase of root biomass under the wet treatment and 28% under the dry

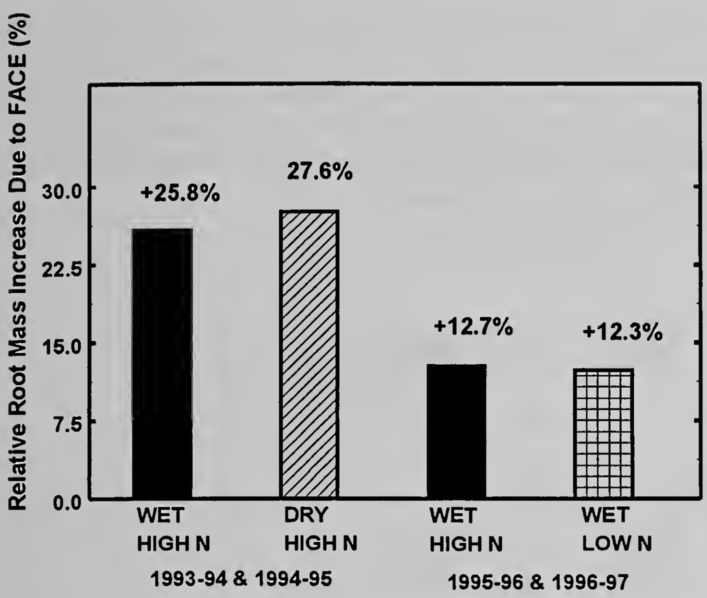

Figure 1: Seasonal response of root biomass to the FACE treatment relative to the ambient Control treatment averaged over sampling dates between tillering and post harvest during the two-year FACE x Water Experiment 1992-93&1993-94 and the two-year FACE x Nitrogen Experiment 1995-96&1996-97.

treatment were observed due to elevated [CO_2] (Fig. 1). In comparison, averaging over the same time period in both years of the FACE x Nitrogen experiment (1995-96&1996-97), the increase of root biomass in the high-[CO_2]-grown plants was lower and reached about 13 and 12% under the high- and low-N treatment, respectively.

Root biomass data obtained during the 1996-97 FACE experiment showed that the root growth varied markedly as the season progressed (Fig. 2). Root mass increased until milk development, when peak living root masses of 90 to 100 g m^{-2} in the top-0.15-m-in-row section were observed Fig.2c). Under low nitrogen, the root mass peak in the lower 0.15-1 m soil depths occurred earlier during anthesis. A root mass increase due to [CO_2] enrichment was observed during the early wheat growth in the inter-row space (Fig.2e). Wheat responded to low nitrogen supply with clearly increased root mass in both CO_2 treatments FACE and Control. In the lower 0.15-1-m, in-row soil space (Fig.2d) FACE and nitrogen stress significantly resulted in higher root mass.

Senescence rates estimated from changes in life root mass appeared to be similar in the FACE and ambient CO_2 treatments (data not shown). Dead root mass data obtained during the 1996-97 season were not significantly different due to higher [CO_2] (Fig.3), but nitrogen stress increased the root mortality slightly during dough development. Therefore, total root growth and senescence during the reproductive period, and thus the carbon input into the soil, occurred according to the changes in live roots.

INTERPRETATION: It appears from this data that carbon translocation through the root system into the soil increases in the future high-CO_2 world; may contribute to an increasing carbon accumulation in the pedosphere.

FUTURE PLANS: The results from the 1995-96&1996-97 FACE wheat experiment will be published. A continued root project within the FACE sorghum experiment is presently planned for the 1999 season.

COOPERATORS: Many individuals played important roles in this research. The authors wish to acknowledge the collaborative efforts of Steve Leavitt (Univerity of Arizona), Bob Roth and Pat Murphree (Maricopa Agricultural Center). We also wish to thank Laura Olivieri, José Olivieri, Matthew Conley, Traci Luna, Carrie C. O'Brien, Justin Gallaher, Ryan Miller, Wayne Jew, Karen Woford, Jon Farr, Lisa Milford, Mary Ann Olson, Kathlene McNamara, JayGanesh Bhatt, Peter Lupke, and Andrew Buege for technical assistance in root sampling, root washing and processing the root core samples.

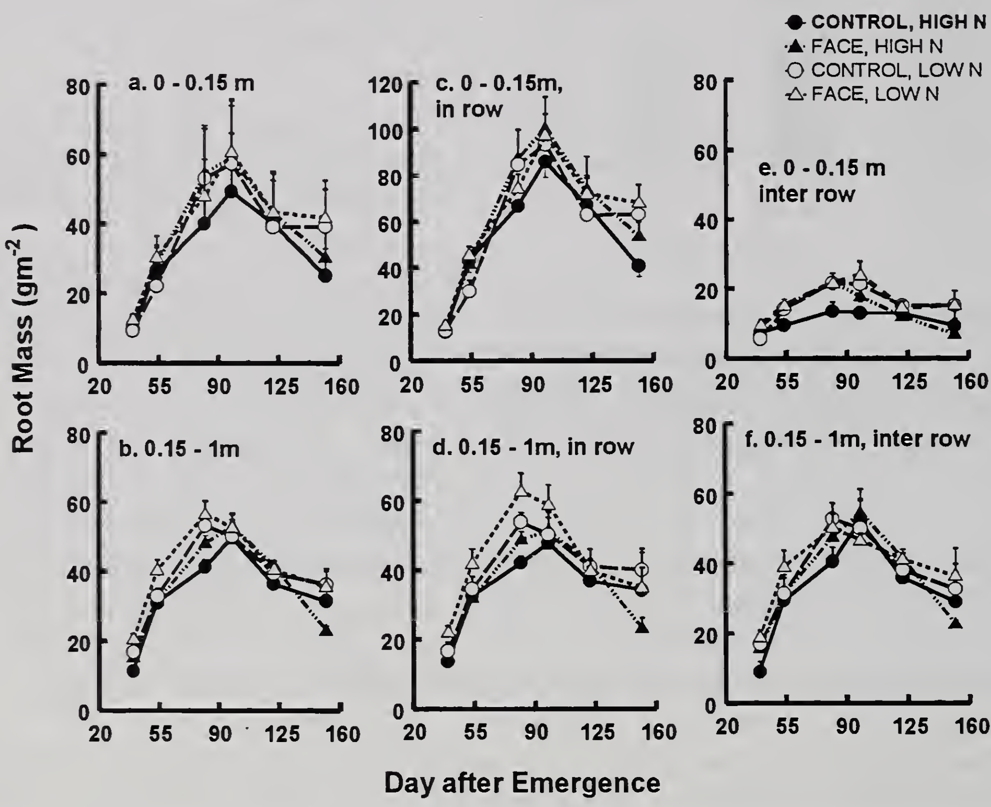

Figure 2: Seasonal course of mean root mass in the FACE x Nitrogen Experiment 1996-97 where day after emergence (40, 54, 82, 98, 122, 152) correspond to tillering, stem elongation, anthesis, milk- and dough development, post harvest; in different soil depth (0 - 0.15 m & 0.15 - 1 m) and two sample positions (in row and inter row).

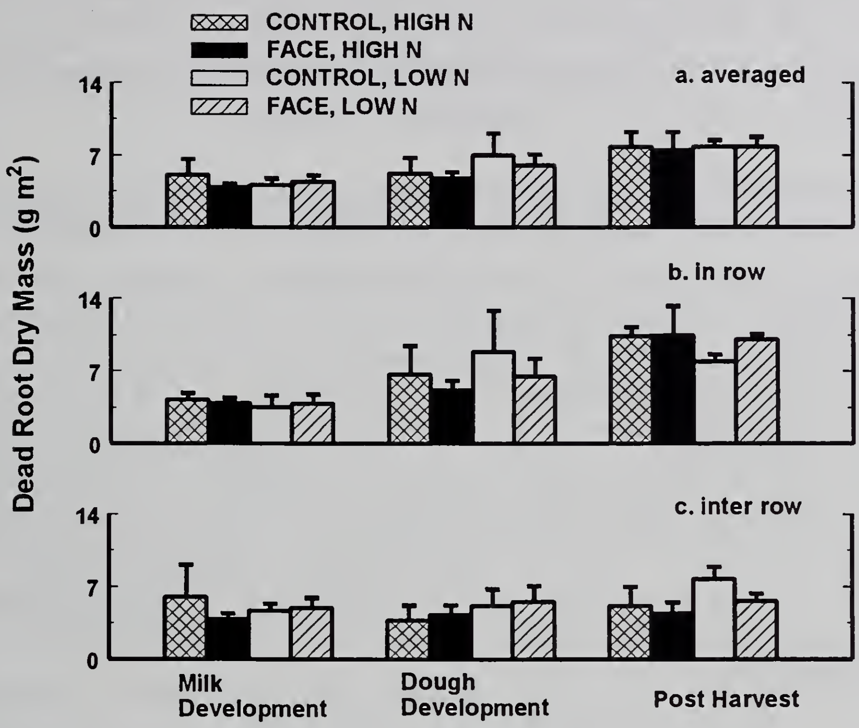

Figure 3: Dead root mass during three reproductive growth stages in spring wheat of the FACE x Nitrogen Experiment 1996-97 averaged over 0-1 m soil depths, a. average over two sample positions, b. in row, c. inter row.

NDVI, fAPAR, AND PLANT AREA INDEX IN THE 1998 FACE SORGHUM EXPERIMENT

P.J. Pinter, Jr., Research Biologist; B.A. Kimball, Supervisory Soil Scientist; R.R. Rokey, Biological Technician; G.W. Wall, Plant Physiologist; R.L. LaMorte, Civil Engineer; N.R. Adam, Plant Physiologist; T.J. Brooks, Research Technician; and S.M. Gerszewski, Biological Technician

PROBLEM: Anticipated increases in atmospheric carbon dioxide (CO_2) and changes in global climate will have important consequences for production agriculture and the world's food supply. The potential effect of these changes on crop productivity has been the subject of extensive research by USWCL scientists. Starting in 1989 and continuing for 7 growing seasons, we have used Free Air Carbon dioxide Enrichment (FACE) technology to study the effects of supra-ambient concentrations of CO_2 on the agronomy and final yields of cotton and spring wheat. Evidence from these experiments and similar studies at other FACE sites around the world have revealed positive effects of elevated CO_2 on the productivity of C_3 plants under natural field conditions. However, the effects of elevated CO_2 on C_4 crops grown in a production environment without the use of chambers remain largely speculative. During the 1998 summer and fall growing seasons, we used FACE technology to examine the interactive effects of elevated CO_2 and water stress on grain sorghum, a globally important C_4 food crop. This report discusses preliminary results from that experiment using several non-destructive methods to infer canopy development and light absorption.

APPROACH: Sorghum (*Sorghum bicolor* L. Dekalb Hybrid DK54) was sown (10.6 kg ha^{-1}; ~129,000 seeds ha^{-1}) in north-south rows spaced ~0.76 m apart at The University of Arizona Maricopa Agricultural Center (MAC) on July 15-16, 1998. Emergence of seedlings occurred on or about July 30, 1998; density was about 90,000 plants ha^{-1}. Plants were exposed to ambient (Control, ~370 $\mu mol\ mol^{-1}$) and enriched (FACE, +200 $\mu mol\ mol^{-1}$ above ambient) CO_2 levels; treatments were replicated four times. CO_2 treatment plots were split in half to test the effect of different flood irrigation regimes on sorghum response to CO_2. Additional experimental details can be found in Kimball *et al.* "Progress and Plans for the FACE Project" in this volume.

NDVI. Canopy reflectance factors were obtained several times per week using a handheld radiometer (Exotech, Inc., Gaithersburg, MD) equipped with 15° fov optics. Twenty four measurements were taken along a 7 m long transect on the north edge of the no-traffic, final harvest area in each treatment combination and replicate. Data were obtained at a time corresponding to a nominal solar zenith angle of 45°. Red (0.63 to 0.69 µm) and near-infrared (NIR, 0.78 to 0.89 µm) reflectance factors were used to compute the Normalized Difference Vegetation Index:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{red})}{(\mathrm{NIR} + \mathrm{red})}$$

fAPAR. Incident (I), transmitted (T), and reflected (R) light in photosynthetically active wavelengths (PAR, 0.4 to 0.7 µm) were measured just prior to midday (1100-1215h MST) at 2 to 3 week intervals during the season using an Accupar sensor (Decagon Instruments, Inc., Pullman, WA). Measurements

were taken above and below the plant canopy in six adjacent rows along the north edge of the final harvest area. The 80 cm-long sensor was oriented perpendicular to plant rows. Data were recorded separately for each 5 cm segment of the sensor. Reflected PAR was also obtained over a bare soil plot ($RPAR_s$). The fractional amount of PAR ($fAPAR_c$) was computed using a light balance equation:

$$fAPAR_c = 1 - \left(\frac{TPAR_c}{IPAR}\right) - \left(\frac{RPAR_c}{IPAR}\right) + \left(\frac{TPAR_c}{IPAR}\right) * \left(\frac{RPAR_s}{IPAR}\right)$$

where the subscripts c and s refer to the sorghum canopy and a bare soil plot, respectively.

<u>PAI.</u> A Plant Canopy Analyzer (LAI-2000, LICOR Inc., Lincoln, NB) was used to obtain data on plant area index (PAI). Data were collected shortly after dawn at 1-2 week intervals during the season. The sensor was deployed between six adjacent rows on the north edge of the final harvest area. The sensor and canopy were shaded from direct beam solar radiation with a manually positioned, opaque panel measuring 1 by 1 m and held at a distance of 5 to10 meters from the optics. The PAI parameter was determined from a total of 3 measurements above the canopy and 18 below the canopy in each plot. A radiative transfer algorithm computes PAI from canopy light interception at 5 different angles of incidence on the fish-eye like sensor (148° field-of-view).

FINDINGS: <u>NDVI.</u> The seasonal NDVI data are shown in Figure 1. The upper panel of this and subsequent figures shows the mean ± 1 standard error of each treatment combination (abbreviations refer to: CD, Control Dry; CW, Control Wet; FD, FACE Dry; FW, FACE Wet). The bottom panel shows the mean of each treatment relative to the value observed in the Control Wet treatment. The seasonal trajectory of the NDVI revealed several distinct phases. First there was an early season phase where the NDVI signal was dominated by reflectance of bare soil and modulated by seedlings that were slowly increasing in size. This was followed by a rapid increase in NDVI as the plants entered an exponential growth phase. Next, we observed a plateau in NDVI values which started about 4-5 weeks before panicle emergence (Day of Year, DOY, 270-280) in the wet treatments. After panicle emergence, there was a slight decrease in NDVI which continued as the grains began early maturation. This was followed by a much steeper NDVI decline after a moderate frost damaged many of the upper canopy leaves on November 11 (DOY 315). The relative NDVI data (shown in the lower panel) emphasize the major separation between the wet and dry irrigation treatments during the middle portion of the season. There were also large differences in NDVI between Control and FACE CO_2 in the wet irrigation treatment from about the 3rd though 6th weeks of growth. Finally, towards the end of theseason, the relative plots show that the dry treatments appear to have

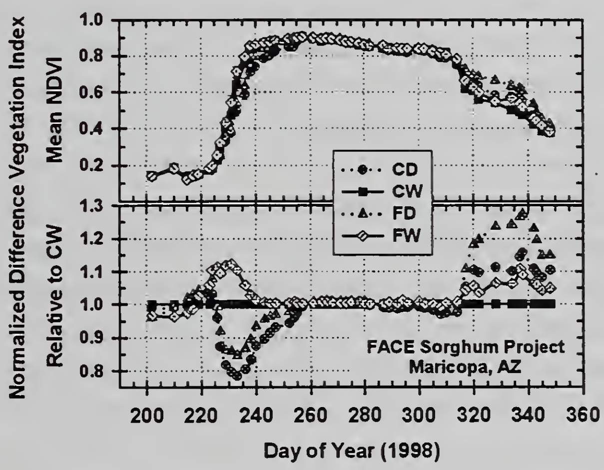

Figure 1. The normalized difference vegetation index during the FACE '98 Sorghum experiment.

suffered the least amount of damage from the mid-November frost event.

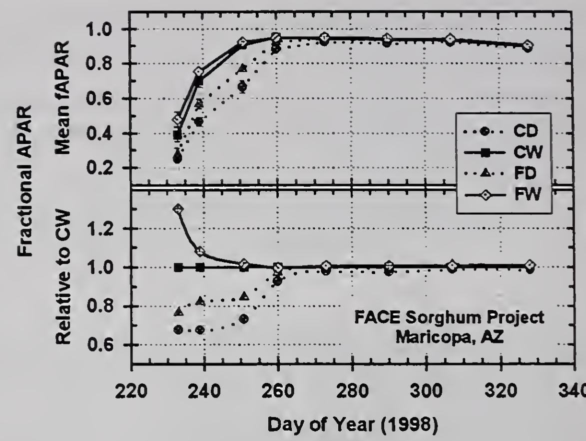

Figure 2. Fraction of absorbed photosynthetically active radiation (fAPAR) during the FACE '98 Sorghum experiment.

fAPAR. Data on canopy PAR absorption were first obtained with the Accupar sensor beginning in mid-August (DOY 230), about 6 weeks after emergence (Fig. 2.). From that point in the season until the plants completely covered the soil in mid-September, we observed rapid increases in midday canopy fAPAR and significant differences were noted between wet and dry treatments. Under the dry irrigation regime, fAPAR in the elevated CO_2 treatments was consistently larger than that of the Control treatments. Although elevated CO_2 appeared to enhance fAPAR of plants given ample supplies of water, this difference was evident for only the first 2 measurement dates. By late September, fAPAR of all the plots had reached a plateau, remaining relatively constant until late grain filling. At season's end, $fAPAR_c$ measured with the Accupar did not drop significantly, despite the fact that there was less green leaf material and an increasing proportion of the incident PAR was being intercepted by non-photosynthesizing canopy elements. During this time we observed differences between irrigation treatments, but clear separation between CO_2 treatments was not evident.

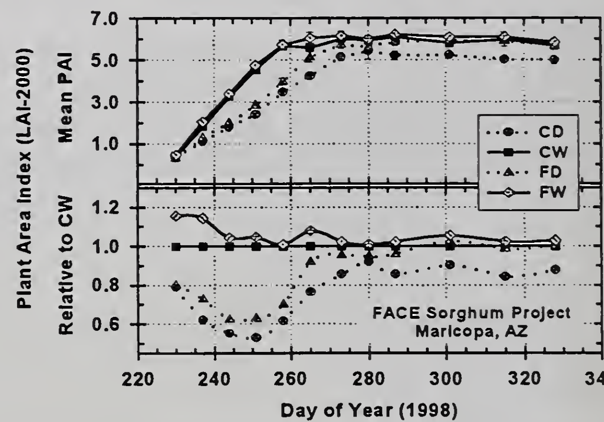

Figure 3. Plant area index measured during the 1998 FACE Sorghum experiment.

PAI. The LAI-2000 measurements showed significant differences between irrigation treatments in the rate of plant canopy development (Fig. 3). We observed a steady increase in PAI in the wet treatments up until mid-September, and then it leveled off at about 6 units both in elevated and ambient CO_2 treatments. PAI in the dry treatments also increased in a regular fashion, albeit at a noticeably slower rate. By early September, the canopy in the dry treatments had a PAI that was only 60% of that observed in the wet treatments. Elevated CO_2 appeared to have stimulated PAI in the wet treatments during the early part of the season. In the drier treatments we found small but significant differences between FACE and Control CO_2 levels on most measurement dates.

INTERPRETATION: The NDVI has been well-correlated with the amount of green biomass in many plant species. Perhaps more importantly, we have shown that a significant positive relationship exists between NDVI and the fraction of incident photosynthetically active radiation absorbed by the sorghum canopy (data not shown here). Thus, one of the most significant implications of these data is that the extra CO_2 stimulated early season plant growth and increased the amount of PAR that was captured by the sorghum canopy for potential use in photosynthesis. During previous FACE experiments with cotton and wheat, we had noted a similar CO_2 enhancement of early season fAPAR as well as green biomass and green leaf area index (LAI). Thus, this seems to be common response for the crops we've studied so far,

regardless of whether they have C_3 or C_4 physiology. The CO_2 advantage in PAR absorption disappeared as the plants approached 100% cover because NDVI and light absorption both approach assymptotic limits and the controls caught up with the FACE treatment. Mid-season convergence did not necessarily imply similar green biomass levels between CO_2 treatments because of NDVI saturation phenomena. In the field, we observed that the plants in the dry treatments were visually smaller and lagged behind the those in the wet treatments. The NDVI data confirmed our visual assessment that early season development of the photosynthesis "factory" was greatly reduced by water stress. However, when the water stress was relieved by precipitation and/or irrigation events, the plants in the dry plots rebounded quickly and eventually approached the same NDVI values as the wet plots. For the first half of the season, our interpretation of the fAPAR and PAI data was very similar to the NDVI. Both showed significant differences between irrigation treatments and slight differences due to elevated CO_2. At the end of the season, however, it was apparent that fAPAR and PAI are relatively insensitive to changes in green canopy biomass and don't convey much biologically significant information.

We found that the NDVI was a very powerful, cost-effective approach for evaluating the effect of experimental treatments on the size of the photosynthetically active canopy and its persistence through the season. Statistically, this non-invasive index offered a tremendous advantage over labor intensive plant sampling methods because 1) the sample size was much larger, and 2) the same population of plants was measured repetitively over the season thus eliminating the plant-to-plant variation that makes traditional sampling methods inherently more variable. Inasmuch as neither the Accupar nor LAI-2000 approach was quite as robust as the NDVI in terms of sample size or frequency of measurement, it is not surprising that the small differences in fAPAR and PAI between CO_2 treatments often had overlapping standard errors. A further disadvantage of the Accupar and LAI-2000 instruments is that it was very difficult to make measurements when plants were small. For example, we found that the size of the sensor itself precluded reasonable measurements until the plants were about 5 weeks old. Biologically significant interpretation of fAPAR and PAI data are further complicated late in the season by the fact that these sensors are affected by the presence of senescent leaves, stems, and panicles and thus do not represent the size of the photosynthetically active factory accurately. Neither fAPAR nor PAI showed a measureable response when frost killed many of the upper canopy leaves. By contrast, NDVI measurements could be made throughout the entire season and were very sensitive to the changes caused by the November frost.

FUTURE PLANS: Analysis of these data are continuing. Actual comparisons between LAI-2000 value and LAI obtained via destructive sampling techniques will be performed. Methods will be sought to extend the Accupar-derived fAPAR versus NDVI relationship beyond anthesis so that NDVI can be transformed into a biophysical parameter having biological significance for the entire growing season. NDVI will also be used to confirm whether the experimental treatments or the blower apparatus itself has an influence on end-of-season rates of canopy senescence. Similar measurements will be carried out during the 1999 FACE Sorghum experiment.

COOPERATORS: Collaborators include M. Ottman, A. Matthias, S. Leavitt, D. Williams and T. Thompson from The University of Arizona; B. Roth and J. Chernicky from MAC; and K. Lewin, J. Nagy, and G. Hendrey from Brookhaven National Laboratory. We also wish to thank J. Triggs, and P. Bierly for technical assistance in the field. See Kimball *et al.* "Progress and Plans for the FACE Project" in this volume for a more complete listing of cooperators.

DAYTIME CO_2 AND NIGHTTIME BLOWER EFFECTS ON CANOPY TEMPERATURES AND FROST DAMAGE DURING THE 1998 FACE SORGHUM EXPERIMENT

P.J. Pinter, Jr., Research Biologist; B.A. Kimball, Supervisory Soil Scientist; R.L. LaMorte, Civil Engineer; and T.R. Clarke, Physical Scientist

PROBLEM: The Free-Air Carbon dioxide Enrichment (FACE) approach was originally developed to expose plants to elevated levels of CO_2 under natural field conditions while minimizing the perturbations in light, temperature, humidity, and wind that often confound results of fumigation experiments in open-top chambers or greenhouses. With the FACE approach, there are no walls to interfere with light distribution or disrupt the wind. Instead, CO_2-enriched air is released at the perimeter of circular plots, and natural wind patterns are depended upon to disperse the CO_2 evenly across the experimental area. This new technology has made it possible to make realistic assessments of the effects of anticipated 21st century atmospheric CO_2 concentrations on growth and yields of agricultural crops growing in large scale production fields.

Our past FACE studies have shown that elevated CO_2 induces partial stomatal closure. This reduces leaf transpiration rates and increases daytime temperatures of cotton and wheat canopies on the order of 0.5 to 1.0 °C. However, under calm, nighttime wind conditions found at Maricopa, Arizona, we also observed that the blowers used to inject CO_2 in the FACE arrays exerted subtle effects on the microclimate in a manner analogous to wind machines used for orchard frost protection. Wheat plots equipped with blowers had nighttime foliage and air temperatures that were 0.6 to 1.0 °C warmer than controls without blowers. This blower-induced temperature anomaly also altered dewfall patterns (leaf wetness was reduced 30%), accelerated plant development (anthesis occurred 4 days earlier), and hastened senescence as compared with the normalized difference vegetation index (NDVI). We found that natural winds and advection appeared to overcome the blower effect during daytime hours. Intrigued by these phenomena and seeking to explore them further, we deployed a thermal scanner from a helicopter during the FACE experiment with grain sorghum. Here we display thermal imagery obtained during one midday and two predawn periods in 1998 and also present data on late-season frost damage sustained by the crop.

APPROACH: Sorghum (*Sorghum bicolor* L. Dekalb Hybrid DK54) was sown in north-south rows spaced ~0.76 m apart in a 10-ha field at The University of Arizona Maricopa Agricultural Center (MAC). Emergence of seedlings occurred on or about July 30, 1998; density was about 90,000 plants ha^{-1}. Plants were exposed to ambient (Control, ~370 $\mu mol\ mol^{-1}$) and enriched (FACE, +200 $\mu mol\ mol^{-1}$ above ambient) CO_2 levels from emergence until seed maturity in mid-December. There were four FACE and four Control rings. Each array was ca. 25m in diameter, separated from adjacent arrays by about 100m, and equipped with identical blower systems. The only difference between FACE and Control arrays was that pure CO_2 was injected into the blower airstream in the FACE plots. The CO_2 treatment plots were further split in half to test the effect of different flood irrigation regimes. Ancillary details can be found in Kimball *et al.* "Progress and Plans for the FACE Project" in this volume.

Imagery was obtained over the FACE field on 3 dates in 1998 using a HgCdTe thermal infrared scanner (Model 760, Inframetrics, Inc., Billerica, MA) equipped with a closed cycle, Stirling microcooler which

enabled measurement of radiant energy in the 8-12 μm region of the spectrum. The scanner provided thermal resolution as fine as 0.2 °C and recorded dynamic imagery at video rates on Hi-8 magnetic tape. The scanner's camera was equipped with a normal (1x) lens which provided an instantaneous field of view (*i.e.* pixel size) of 1.8 milliradians and an overall image field of view of approximately 15 by 20 degrees. It was deployed manually at an oblique angle from the open door of a light helicopter that was flown between 150 m and 1000 m above ground level. The first mission was flown on Oct. 13 about 1 hour after solar noon. Subsequent flights occurred just prior to dawn on Oct. 14 and Nov. 19. Single frame images were extracted from continuous video data, then digitized, color coded, and analyzed using ThermoGRAM software from Inframetrics.

Frost damage to the sorghum canopy was estimated on November 24, 1998, about 2 weeks after several mornings when air temperatures at the field dropped slightly below freezing. The top four leaves on four randomly selected plants in each plot were given scores between 0 (no damage) and 10 (100% damage) based on their visual appearance. Additional observations were made in previously established field plots that were positioned midway between the FACE and Control arrays in the wet and dry splits of each replicate.

FINDINGS: Several representative thermal images obtained during the experiment are shown in the Appendix of this report. In the color imagery, violet and dark blue are used to represent cooler temperatures while green, yellow, and red are used to indicate increasingly warmer temperatures. Figures 1 and 2 show differences between Control and FACE plots in data obtained during the afternoon flight on Oct. 13 (DOY 286). The sorghum plants had just completed anthesis, air temperature was about 33 °C, and there was a light cirrus cloud coverage and a slight NW wind. We did not observe any systematic differences between canopy temperatures of sorghum growing inside or outside the Control (ambient CO_2) plot manifolds (Fig. 1). However, plants within the FACE (CO_2 enriched) manifolds were about 1 °C warmer than those growing outside the arrays (Fig. 2). Figures 3, 4, and 5 were obtained the next morning before dawn (DOY 287). Air temperatures were about 14 °C, skies were clear, and there was an intermittent light breeze from the south. This imagery set shows a distinct increase (~0.5 °C) in canopy temperature inside the manifolds of both the Control (Fig. 3) and FACE arrays (Fig. 4) compared with areas outside of the rings. The crescent-shaped pattern of warmer temperatures along the windward (left hand) edge of the FACE array (Fig. 4) was typical of all blower-equipped arrays and much more evident in the moving video imagery. This unique pattern was a result of air and CO_2 injection from the vertical standpipes on the upwind side of each array. Figure 5 shows imagery from a Control array wherein we had manually turned off the air injection system. No temperature difference was detected between the areas that were inside versus outside the manifold.

The following month during grain fill, we repeated the pre-dawn flight with the thermal scanner and captured imagery from the field. Results on this calm night were similar to those from the earlier flight when there was a light breeze. Sorghum in plots equipped with operational blowers had temperatures that were slightly warmer than plants outside of the arrays. In fact, Figure 6 shows simultaneous imagery of all four arrays in replicates 1 and 2 but only three arrays are evident (in this image, warmer temperatures are brighter). This was because we had intentionally turned off the blower in the Control plot located in the lower left corner of this figure. Even though the black and white image makes it easy to spot subtle differences in temperature in 3 of the arrays, it is very difficult to discern the position of the 4th because there is no artificial air movement. The crescent-shaped thermal pattern that was so obvious during the

first predawn flight was not seen in this imagery. Instead, canopy temperatures were more uniformly warm across each circular array with a hint of a cooler region near the center. This was because wind speeds were less than 0.4 m s^{-1}, and the CO_2-enriched air was being released from every other standpipe around the array. Towards the end of this flight, we turned the blower in the Control plot of replicate 1 back on, and within several minutes the imagery revealed warmer temperatures in this plot also.

The frost damage we observed in upper canopy leaves was notably less severe when plants were exposed to moderate water stress (Table 1). Damage was also related to whether or not the plots were equipped with blowers. In fact, plants in the FACE and Control rings within the dry treatment sustained less than half the damage as the dry, mid-field plots without blowers. In the wet irrigation treatment, FACE and Control plants experienced about 70% of the damage received by their mid-field counterparts.

Table 1. Frost Damage to Upper Canopy Leaves
24 November 1998

	Control Plots (with blowers)		**FACE Plots** (with blowers)		**Mid-Field** (no blowers)	
Dry Irrigation Treatment	**46 %**	± 8.7 %	**22 %**	± 4.0 %	**89 %**	± 1.9 %
Wet Irrigation Treatment	**68 %**	± 5.0 %	**64 %**	± 10.0 %	**95 %**	± 1.7 %

INTERPRETATION: The thermal phenomena we observed in the FACE sorghum plots were very similar to those documented using conventional micrometeorology and thermal infrared sensors during the FACE cotton and wheat experiments. During the day, we found plant temperatures in the CO_2-enriched arrays that were elevated compared with plants outside the arrays and plants in the Control plots. This was a genuine physiological response to CO_2 caused by partial stomatal closure. The fact that the blower-equipped control plots were thermally indistinguishable from areas outside of the arrays reinforces our previous observations that natural wind and convection patterns simply overwhelm the blower effect except under the most stable atmospheric conditions. At night, however, the blower effect is more noticeable, resulting in canopy temperatures that are slightly warmer. That this small temperature difference can have a significant biological effect was emphasized towards the end of the 1998 experiment when air temperatures hovering just below freezing caused some frost damage to our sorghum field. We observed that the foliage damage was less severe within the FACE and Control plots than it was in mid-field areas that were outside the blower-equipped arrays.

FUTURE PLANS: A manuscript documenting the biological and micrometeorological changes associated with the blowers used in the FACE apparatus is being prepared for publication. Information will be used to help us and others make intelligent decisions regarding enrichment strategies for FACE experiments at different sites around the world.

COOPERATORS: Collaborators include M. Ottman, A. Matthias, S. Leavitt, D. Williams and T. Thompson from The University of Arizona and K. Lewin, J. Nagy, and G. Hendrey from Brookhaven National Laboratory. See Kimball *et al.* "Progress and Plans for the FACE Project" in this volume for a more complete listing of cooperators.

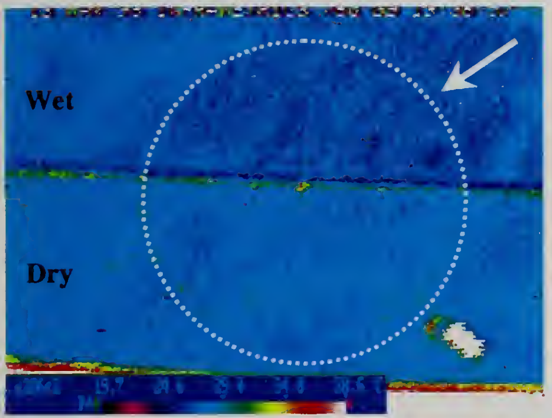

Fig. 1. Thermal image of Control 2 at ~1330h on DOY 286. Arrow shows wind direction and points to NW edge of manifold. No systematic difference in temperature is evident between sorghum inside and outside of the circular manifold (dotted circle).

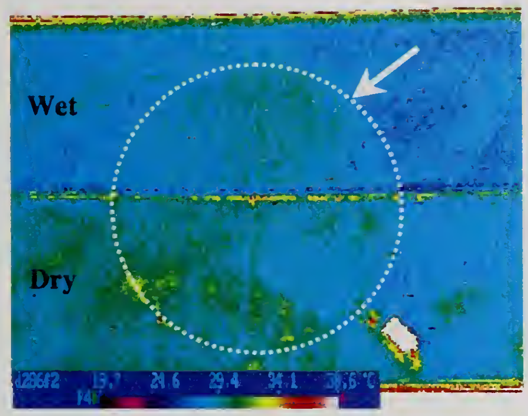

Fig. 2. Thermal image of FACE 2 at ~1330h on DOY 286. Arrow shows wind direction and points to NW edge of manifold. The sorghum canopy inside the manifold (dotted circle) is about 1 C warmer than outside.

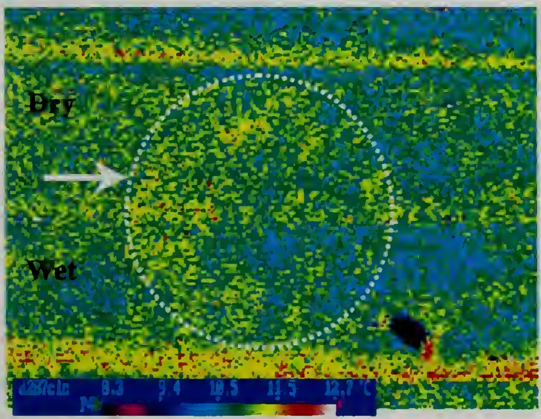

Fig. 3. Thermal image of Control 1at ~0549h on DOY 287. The arrow shows wind direction and points to the S edge of the manifold. There is a slight difference in temperature evident as a crescent shaped area on the upwind side of the plot.

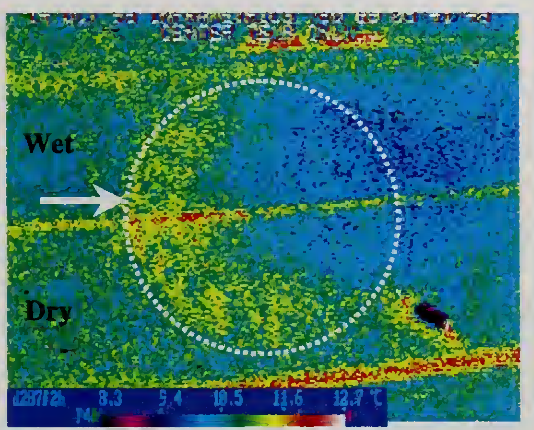

Fig. 4. Thermal image of FACE 2 at 0541h on DOY 287. The arrow shows wind direction and points to the S edge of the manifold. There is a slight difference in temperature evident as a crescent shaped area on the upwind side of the plot.

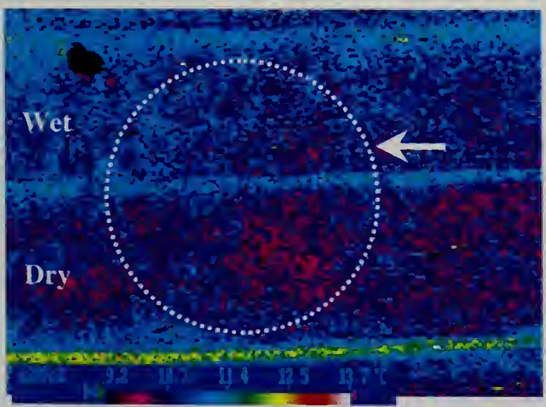

Fig 5. Thermal image of Control 2 at 0541h on DOY 287. Blower fans are turned off. The arrow shows wind direction and points to the S edge of the manifold. No difference in temperature is evident between sorghum inside and outside of the circular manifold.

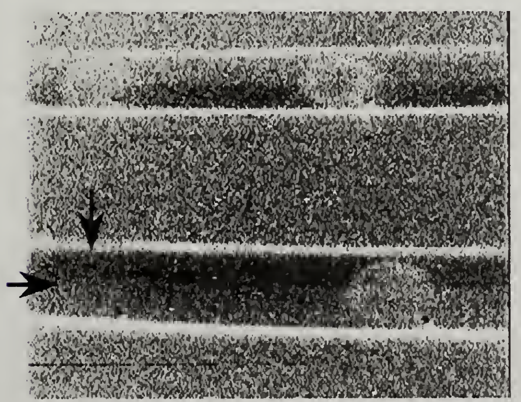

Fig. 6. Thermal image of Replicates 1 & 2 at 0551h on DOY 323. Clockwise from the upper left corner are FACE 2, Control 2, and FACE 1. The blower fans were turned off in Control 1 which is located in the lower left corner (arrows) but cannot be seen clearly in this image.

FARM MANAGEMENT DECISION SUPPORT USING A REMOTE SENSING AND MODELING APPROACH

CONTENTS

FARM MANAGEMENT DECISION SUPPORT USING A REMOTE SENSING AND MODELING APPROACH

MISSION

Evaluate the potential for making real-time farm management decisions using imagery obtained with multispectral cameras and thermal infrared scanners. Develop an integrated system for acquiring imagery and assembling the relevant information in a format useful for prescription farming applications. Demonstrate the economic and environmental benefits of automated remote sensing systems for farm management.

MAC-ATLAS: VERIFICATION AND VALIDATION OF A NASA AIRBORNE SCANNER FOR FARM MANAGEMENT APPLICATIONS

M.S. Moran, T.R. Clarke, J. Qi, Physical Scientists;
E.M. Barnes, Agricultural Engineer; and P.J. Pinter, Jr., Research Biologist

PROBLEM: Research studies of remote sensing applications to agricultural management generally have stringent image acquisition and resolution requirements. To investigate seasonal crop and soil conditions, images must be acquired at critical phenologic stages, such as prior to planting, at time of plant emergence, prior to canopy closure, at plant maturity, late in the season prior to harvest, and at senescence. Additional requirements include quick image turnaround (1-7 days), fine spatial resolution (ranging from 2-20 m), multispectral imaging (including visible, near-infrared and thermal spectral bands), and image units of reflectance and temperature, not simply digital numbers (*dn*).

This restrictive set of data requirements is rarely met by most aircraft- and satellite-based sensors. An exception is the fleet of NASA aircraft-based sensors which include the Airborne Terrestrial Land Applications Scanner (ATLAS) aboard the Lear Jet (Table 1). A Non-Reimbursable Space Act Agreement was signed between the USDA-ARS U.S. Water Conservation Laboratory (USWCL) and NASA Stennis Space Center (SSC) to investigate the use of ATLAS spectral imagery for farm management applications. Through this agreement, SSC agreed to provide ATLAS imagery of the Maricopa Agricultural Center (MAC) on six dates selected by USWCL scientists to correspond with the cotton and sorghum growing seasons: April 14, June 9, June 23, July 7, Aug 4, and Sept 17, 1998. USWCL agreed to provide a critical review of ATLAS image products, provide on-the-job training for SSC personnel in precision agriculture and ground data collection, and present results at the Verification and Validation Symposium at SSC.

Table 1. Specifications of the ATLAS sensor aboard the NASA LearJet.

Spectral Coverage (in micrometers):		
Visible and Near Infrared	Shortwave Infrared	Thermal Infrared
Ch. 1: 0.45-0.52	Ch. 7: 1.55-1.75	Ch. 10: 8.20-8.60
Ch. 2: 0.52-0.60	Ch. 8: 2.08-2.35	Ch. 11: 8.60-9.0
Ch. 3: 0.60-0.63		Ch. 12: 9.0-9.4
Ch. 4: 0.63-0.69		Ch. 13: 9.6-10.2
Ch. 5: 0.69-0.76		Ch. 14: 10.2-11.2
Ch. 6: 0.76-0.90		Ch. 15: 11.2-12.2
Spatial Specifications:		
Field of View: 72 degrees Inst. Field of View: 2.0 mrads	Pixels/Line: 640 ground scene and 3 calibration source pixels Ground Resolution: 2.5-25 m	
Calibration: Thermal: Blackbody; Visible and Near Infrared: Integrating Sphere		

APPROACH: The ATLAS mission request was designed best to suit agricultural research. It required two days advanced notification of overflight, 2.5 m data resolution, flightline spacing to achieve 20° field-of-view (FOV) over all MAC, color infrared (CIR) photography to support all flights, and coordination between the USDA ground crew and SSC aircraft crew. This set of specifications resulted in a set of ten parallel, E/W flightlines covering MAC with nearly 75% flightline overlap. The extreme image overlap was requested to ensure that every site on the farm was imaged with a sensor look angle < 10°.

During each of the six ATLAS overpasses, a standard set of measurements was made on the ground to verify image quality and document crop and soil conditions:

• Calibrated reference tarps of 8x8m dimension were deployed to provide targets of known reflectance for conversion of ATLAS *dn* to units of surface reflectance and temperature.

• Measurements with yoke-based radiometers (4-band and 8-band radiometers and an infrared thermometer) were made over a near-full-cover field of alfalfa and a large packed-earth landing strip.

• On each overpass date, a three-person crew surveyed the entire farm to document the following information for each border of each field at MAC: crop type, crop growth stage, percent vegetation cover, soil moisture, soil roughness, crop row direction; and comments (pests, litter, wilting) and noted anomalies (see graphic illustration in Figure 1).

• The bidirectional reflectance of vegetated targets and the packed-earth landing strip was measured using an radiometer mounted on a hinged boom that could measure reflectances of one target at a variety of view angles along a single plane. Measurements were made of surface temperature (8-12 μm) and surface reflectance in 250 wavelength bands in the visible and near-infrared spectrum at a variety of sites, including ponds, burned fields, bare soil, and fields of differing crop types, vegetation cover and row direction.

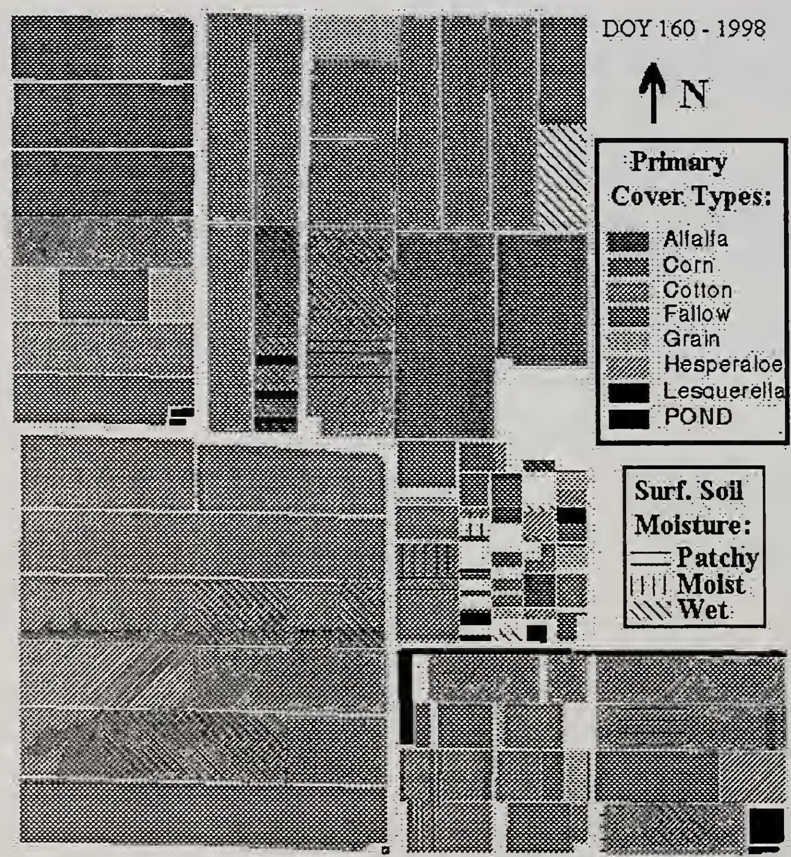

Figure 1. Example of MAC survey maps of crop and soil conditions.

In association with the USDA-SSC effort at MAC, a NASA-funded MODIS Instrument Team investigation was designed to acquire a season-long dataset of field radiometric measurements and biophysical data including fraction absorbed photosynthetically active radiation (fAPAR), leaf area index (LAI), and above-ground biomass.

RESULTS: At this time, we have processed the ATLAS images from only one overpass (9 June 1998); consequently, the following results are preliminary. The first step in our analysis was simply to assess 1) the appropriateness of the sensor gains and offsets, and 2) the shifts in gain and offset from one flightline to the next. Regarding gains and offsets, we found that the offset for the visible bands was rather large (about 50-100 *dn*) and all bands had significant saturation at *dn*=255 over agricultural targets. This level of saturation was unacceptable for agricultural research and most operational applications. Furthermore, we determined that the gain of some bands had been changed in-flight to avoid apparent *dn* saturation.

A primary goal of our on-site ground measurements was to produce a linear relation between *dn* and reflectance or temperature that could be applied to data from all flightlines to retrieve reflectance and temperature from image *dn*. Our preliminary analysis showed that a linear fit was suitable for ATLAS data only when the *dn* did not approach saturation (e.g., *dn*=255); we found a non-linear sensor response for the high surface reflectance range. This non-linear response is common in most radiometers and can be resolved by setting the gains and offsets to avoid very low and very high *dn*.

To assess the view-angle effects of the wide FOV ATLAS imagery, *dn* values for two sites (the landing strip and a vegetated alfalfa field) were extracted from the overlapping sections of five flightlines. Based on the location of the site within the flightline, the sensor view angles (ranging from +26° to -26°) for each measurement were computed. The trend of ATLAS *dn* with view angle is consistent with expectations: the *dn* was relatively low in the forward-scattering direction and high in the back-scattering direction (Figure 2). The magnitude of the effect was substantial; that is, for both the landing strip and the alfalfa, the measured *dn* could vary by up to 40 counts due simply to the location of the site in the ATLAS flightline.

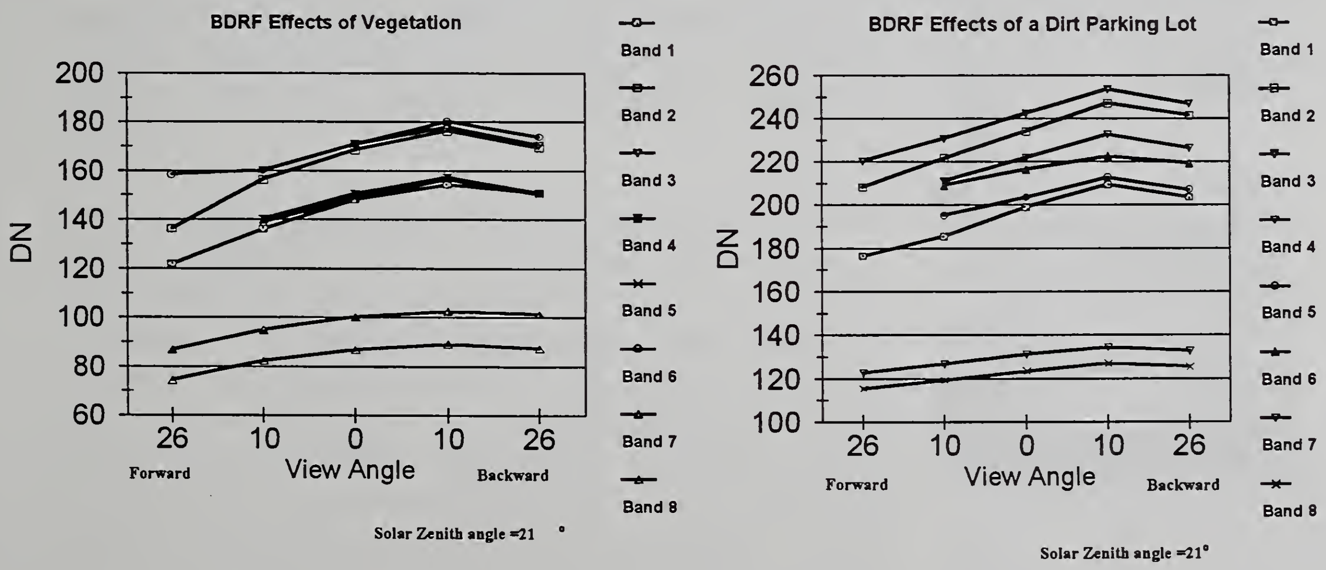

Figure 2. ATLAS measurements of surface bidirectional reflectance of a cotton canopy and a packed-earth landing strip in the eight reflective spectral bands (labeled 1-8) at about 11.0am along a plane close to the principal plane of the sun.

INTERPRETATION: The logistics of the experiment went well and could serve as an example for planning future remote sensing experiments. The minimum two-day *advance notice* of overflight allowed us to mobilize a large field crew for ground-based measurement. The *precision flights* were reliably on time and on target. The SSC flight crew made a *phone call* to the USDA ground crew on the morning of the overpass to adjust the flight time to avoid cloudy weather. The flight *mission design* was ideal for our agricultural applications; we were able to obtain complete farm coverage with <10 degree viewing angle (to avoid bidirectional effects), complete farm coverage with viewing angles as great as 26 degrees (to study bidirectional effects), repeat flightlines for studies of effects of solar angle variations, and spectral (visible/near infrared/shortwave infrared/thermal) and spatial (2.5 m) resolutions suitable for within-field studies. The *rapid turnaround* time for images and the accompanying reports were very useful for monitoring rapidly changing crop and soil conditions. The *CIR photographs* were most helpful for interpreting the spectral information in the ATLAS images. The *adherence to the schedule* of flights has allowed us to obtain images corresponding to critical crop phenologic stages. The *visits of SSC personnel* to the MAC field site during several overpasses was very useful for both SSC and USDA scientists. The SSC scientists learned the magnitude and limitations of the field effort and the USDA scientists learned more about the image acquisition and processing. This was a very fruitful exchange.

FUTURE PLANS: We plan to continue cooperation with NASA SSC on such image processing issues as geometric correction and radiometric quality, with the possibility of constructing a permanent ground-based reference target at MAC which would circumvent the four-person task of tarp deployment and would allow limited field personnel to make other important measurements.

COOPERATORS: Alfredo Huete, University of Arizona Dept. Soil, Water and Environmental Science; Joe Spruce, Risa Wu, John Foster, Steve Tate, Jeff Jenner and Rodney McKellip, NASA Stennis Space Center.

DEVELOPMENT OF GROUND-BASED MULTISPECTRAL CROP MONITORS

T.R. Clarke, Physical Scientist and E. M. Barnes, Agricultural Engineer

PROBLEM: One of the main barriers to applying remote sensing tools to agricultural management is that the cost of acquiring data often exceeds the perceived economic gain of such information. While work continues on increasing the value of remote sensing products to growers, an alternative is to reduce the cost of the data, hence bringing the expense below the perceived benefit rather than raising the benefit above the cost of acquisition.

The basic operating cost of decision-making remotely sensed information for a grower can be partitioned into sensor and platform cost, platform operation and maintenance, data retrieval, data analysis and information delivery. Aircraft- and satellite- based sensor systems both require imaging sensors for the needed ground spatial resolution which can be expensive, particularly in the mid infrared and thermal infrared parts of the spectrum. The cost of developing, constructing and launching a satellite is extremely high, while maintaining an aircraft and retaining a skilled pilot also requires a substantial investment. Aircraft data must be calibrated, precisely georeferenced, and corrected for within-image bi-directional reflectance variation before any analysis and product algorithms can be applied. Satellite data must be transmitted to a ground station, have systematic errors corrected, and be calibrated to reflectance. Pointable platforms will also require bi-directional reflectance correction.

Figure 1. Fixed-position Crop Monitor

APPROACH: An alternative method of acquiring data is being investigated. The sensors for a ground-based package can be simple, inexpensive, non-imaging radiometers, with the movement of the platform providing the spatial resolution necessary. An agricultural field is often traversed in the normal course of raising a crop; tractors cultivate and apply fertilizers and pesticides several times per season, aerial applicators may visit the field, and lateral move and pivot irrigation systems cover fields with great regularity. These "free rides" could be utilized to provide very economical remotely sensed data to the grower. In addition, many remote sensing applications do not need high spatial

resolution, and a unit mounted on a pole overlooking a large area would suffice.

FINDINGS: To begin investigations into these possibilities, an inexpensive, extremely rugged, lightweight sensor package was needed. Two iterations of such a package have been developed at the U. S. Water Conservation Laboratory in the past three years. The first set of three was used in the 1996 and 1997 cotton seasons. The oblique-looking sensor packages each consisted of green, red, red edge, near infrared and thermal infrared radiometers enclosed in an 8.5-cm.-diameter by 15-cm.-long weatherproof case with an additional up-looking sensor measuring incoming radiation in the reflective bands. These weatherproof sensors were permanently mounted on 5-meter poles and each monitored a 1/10 ha irrigation treatment. Each package cost well under $1,500 in parts.

A new, more rugged package was developed in 1998 for use on moving platforms. Initial tests have been very encouraging, although the calibration of up- and down-looking sensors has not yet been accomplished.

INTERPRETATION: Low cost, rugged sensor systems for ground-based platforms do appear to be a feasible alternative to more complex remote sensing systems. Sensitivity to ambient temperatures in the reflective bands is apparent but can be corrected using the body temperature of the thermal radiometer. A thermistor or thermocouple may be necessary in the up-looking sensor package to compensate for ambient temperature effects in that package. Of the other two main components of the data acquisition system, the differential global positioning system (GPS) will presumably be standard equipment on tractors and aerial applicators of the future, and it may not be necessary on above-ground irrigation systems. Data recording continues to be a major cost, currently running nearly equal to the cost of the sensor package itself. This cost will probably come down in the not-too-distant future.

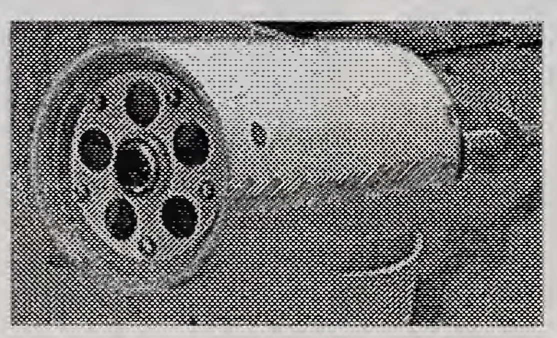

Figure 2. Improved weatherproof sensor package with ports for five reflective bands surrounding a thermal infrared radiometer.

FUTURE PLANS: Further sensor development will concentrate on reducing cost by investigating newer, less expensive thermal infrared detectors, which could reduce the materials cost by half.

COOPERATORS: Dr. Peter Waller and Dr. Chris Choi, Department of Agricultural and Biosystems Engineering, University of Arizona. Dr. Jack Slater, Idaho National Engineering and Environmental Laboratory.

INTEGRATION OF REMOTE SENSING AND GROWTH MODELS TO PROVIDE DECISION SUPPORT FOR PRECISION CROP MANAGEMENT

E.M. Barnes, Agricultural Engineer; P.J. Pinter, Jr., Research Biologist; T.R. Clarke, Physical Scientist; M.S. Moran, Physical Scientist; and Mike Baker, Research Specialist

PROBLEM: Precision crop management (PCM) has been defined as an "information- and technology-based agricultural management system to identify, analyze and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability and protection of the environment" (Robert et al., 1995). Collecting and processing the considerable amount of information required to effectively manage within-field spatial and temporal variability in crop production is a significant task in itself. The next step of applying this information to achieve the desired balance of profitability, sustainability, and environmental protection can become an overwhelming task for the already busy farm manager. The objective of this project is to demonstrate how remotely sensed data, crop models, and decision systems can be integrated to meet the information needs of producers and consultants practicing PCM.

APPROACH: An overview of the framework to provide the integration of remotely sensed data and crop models for decision support is illustrated in Figure 1. The first component, remotely sensed data, is essential because this data can provide complete coverage of a farm at relatively frequent intervals. In order to establish temporally consistent, quantitative relationships between remotely sensed measurements and crop conditions, the data must first be calibrated (Moran et al., 1997a). For satellite and aircraft data, this involves correcting for atmospheric interference, illumination intensity, and solar and viewing angles. Precise georeferencing of the data is required so the data can be directly integrated into a geographic information system (GIS). In the next component, the corrected information is used with a data model to relate the reflectance or radiance to an agronomic parameter. Several relationships have been established between multi-spectral data and parameters that are relevant to PCM (Moran et al., 1997b). For example, remotely sensed data has been found useful to detect crop water stress (Clarke, 1997), map nitrogen deficiencies (Blackmer et al., 1996), and estimate absorbed photosynthetically active radiation (Pinter, 1993). While this is valuable information, it does not provide all the tools necessary for a grower to evaluate management decisions nor does it identify which alternative best satisfies multi-objective criteria. The fourth component (crop models) provides the ability to test different management scenarios on the computer before it is implemented in the field. Because it is usually not feasible to collect enough plant-related

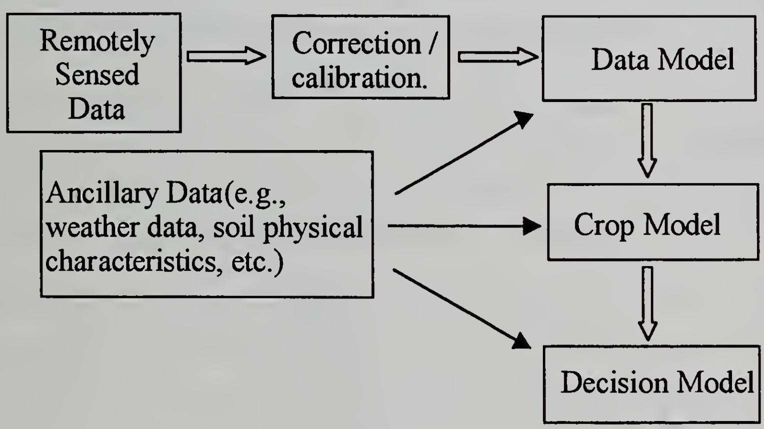

Figure 1: Overview of the integration framework.

data to characterize field scale variability for use in PCM, the remotely sensed data are used as surrogates for crop growth in the model. One approach used to couple the remotely sensed data to a crop model is the use of remotely sensed estimates of leaf area index (LAI) to adjust the crop model's parameters so that its predictions match the field conditions (Barnes et al., 1997). Once the various management alternatives have been simulated with the crop model, the resulting information is then input to a decision model. The decision model used is a fuzzy composite programming (fcp) system similar to that of Hagemeister et al. (1996) capable of processing the multiple criteria set forth in the definition of PCM.

FINDINGS: Initial testing of the system has been conducted using airborne data collected during the 1994 cotton growing season at the Maricopa Agricultural Center. For the test case, a field was selected where differences in crop density assessed from the airborne imagery could be attributed to variations in soil texture based on an existing soil map for the farm. The red and near-infrared bands of the airborne images were used to derive estimates of LAI from an existing empirical relationship. The CALGOS cotton growth model was used because this model was developed to provide reliable predictions under arid conditions (Marani et al., 1992). Current management practices were determined from farm records and input to the crop model. The cotton model's soil parameters were adjusted until predictions of LAI were consistent with the remotely sensed estimates. After this "calibration" process, a higher frequency irrigation management approach was simulated with the crop model. The predictions of yield from the crop model were combined with ancillary data of production cost and crop price to establish the profitability of the different management approaches (including the option of not planting sections of the field). Data on nitrogen leaching and required inputs for the various management scenarios provide the decision model with information on environmental protection of the three

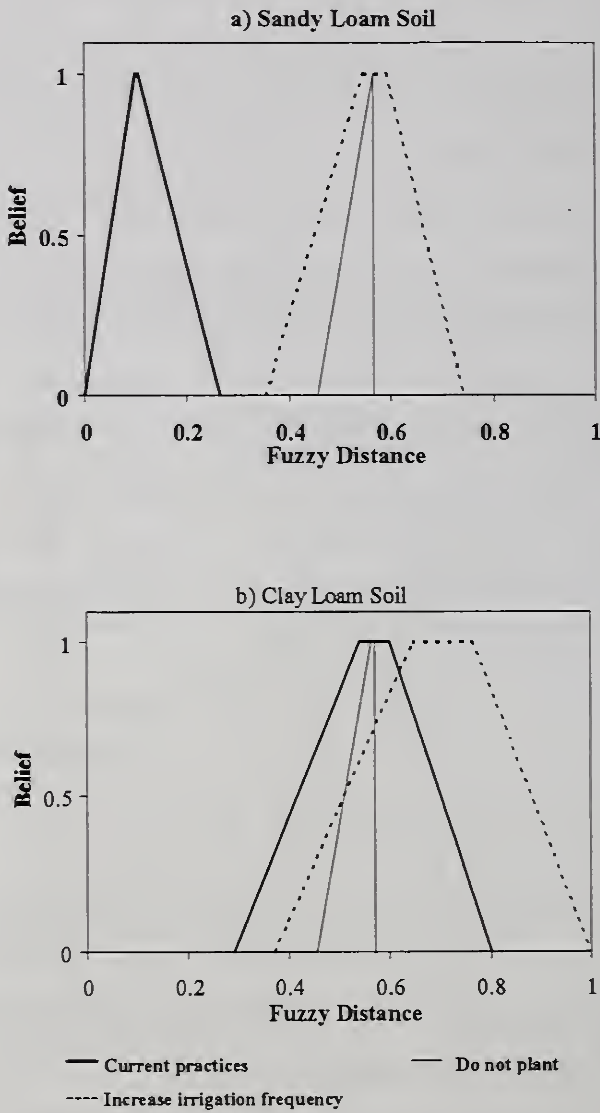

Figure 2: Sample output from the decision model. The y-axis represents the belief that a given scenerio has reached a particular distance towards the ideal solution of 1 on the x-axis.

scenarios. Sustainability of the three systems was subjectively assigned a rating of high, moderate, or poor. The competing interests were compared by normalizing all of the values between 0 and 1 by defining best and worst cases for each input. The decision model also made use of "weighting" factors to define the importance of different objectives. For the test case, a producer's perspective was assumed and the greatest weight was assigned to the profitability. The decision model then ranked the proposed management options in terms of all three criteria, with the resulting output shown in figure 2 for two soil types.

The system does not provide a single "answer"; instead the rankings are presented as fuzzy numbers to reflect the uncertainty of the inputs to the system. The values on the x-axis of the graphs in figure 2 are normalized, with 1 representing an ideal solution. The y-axis represents the "belief" (i.e., relative confidence) that a particular management system has reached a specific level in providing an ideal solution. For example, the "do not plant" (DNP) option covers a smaller range on the x-axis than the other possibilities for both soil types because the uncertainty about the inputs used to describe this management option are very well defined.

For the sandy loam soil, the current irrigation practices are ranked far below the other two options; however, there is less distinction between the DNP and increased irrigation frequency option. There is much less distinction in the rankings of the three alternatives for the clay loam soil. Based on this information, a producer may decide to further evaluate different management approaches for the sandy loam soil and continue current practices over the clay loam.

INTERPRETATION: The approaches taken in this study demonstrate that the integration of remotely sensed data and crop models can lead to a useful tool to assess PCM strategies. One of the powerful aspects of this system is the ability to reduce large amounts of data into a summary chart. This system also provides a method to document the decision making process.

FUTURE PLANS: Future work will focus on expanding the initial test case so that inputs and expenses are described with more accuracy and in greater detail. Additionally this approach will be adapted for application with equipment-mounted sensors and the energy water balance simulation model ENWATBAL (see Clarke et. al., "Development of ground-based multispectral crop monitors" and Barnes et. al., "Development of a modeling and sensor system to provide information for precision crop management" in this report).

COOPERATOR: David Jones, University of Nebraska, Lincoln, NE.

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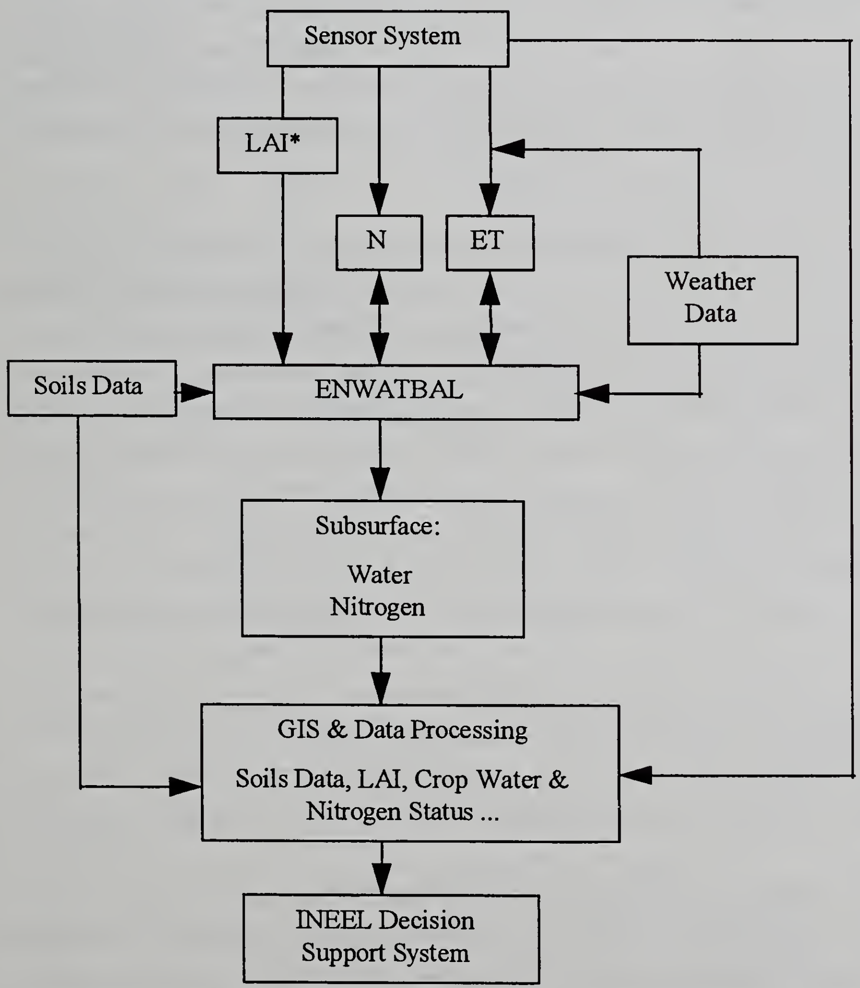
DEVELOPMENT OF A MODELING AND SENSOR SYSTEM TO PROVIDE INFORMATION FOR PRECISION CROP MANAGEMENT

E.M. Barnes, Agricultural Engineer; T.R. Clarke, Physical Scientist; M.S. Moran, Physical Scientist; Stacy Richards, Research Lab Assistant; D.J. Hunsaker, Agricultural Engineer; P.J. Pinter, Jr., Research Biologist; and F.J Adamsen, Soil Scientist

PROBLEM: Precision farm management requires timely, georeferenced information on crop and soil conditions. In this management system, the crop is given what it needs based on the current soil and environmental conditions so that economic return (not necessarily yield) is optimized. Cost efficient methods to provide this information are lacking at the present time. The objective of this project is to provide the tools needed economically to manage crop inputs at a very fine scale (potentially as small as 1 m).

APPROACH: To provide real-time management information, a combination of a sensor- and modeling-based approach is under development. A diagram of the entire system is shown in Figure 1. The first component is a modular reflectance sensor and carriage system that can be mounted on a variety of agricultural equipment, particularly linear or center pivot irrigation rigs (see Clarke et. al., "Development of ground-based multispectral crop monitors" in this report). These sensors examine plants in the thermal and reflected part of the spectrum to detect water and nitrogen stress. One limitation to the sensors is that they will provide data on field conditions only at discrete periods. Therefore, the remotely sensed measurements are combined with the energy and water balance model ENWATBAL (Lascano, et. al., 1987) to provide data at the temporal frequency needed for real-time management decisions. The data from the sensors will also be used to improve ENWATBAL's spatial predictive abilities and to provide a real-time feedback system to insure the model's predictions are



*Notation: LAI = Leaf Area Index; N = Crop nitrogen status; ET = Evapotranspiration

Figure 1. Schematic representation of the proposed system.

accurate. As the system will require and generate extensive amounts of data, new methods for data reduction and archiving are also being developed in this project. One use of the system will be to provide real-time information for use by a decision support system under development by the Idaho National Engineering and Environmental Laboratory (INEEL).

This project is part of a cooperative study, primarily funded by the INEEL. The U.S. Water Conservation Laboratory is providing the expertise on the remote sensing components of the study and assisting in the execution of field experiments to collect the data need to validate and develop the system. The University of Arizona is working on the hardware design of a carriage for the sensor and developing techniques to provide an interface between the remotely sensed data and ENWATBAL. Texas A&M University is providing the expertise on ENWATBAL and conducting a coincident experiment in Texas. The project is also enhanced by the participation of two private companies, Valmont, which is providing a linear move irrigation system for the project, and CDS Ag. Industries.

The first year of the project has focused on the sensor design, testing and development over nitrogen and water treatments in cotton. The experimental treatments were low water, low nitrogen (40 kg/ha of N applied), low water and low nitrogen, and a control (high water x high nitrogen, 80 N kg/ha applied). Each treatment was replicated 4 times in 12 m x 24 m plots organized in a random complete block design. Through boll development, water was applied by surface irrigation, as modifications to a linear move irrigation system to allow applications to selected plots were not complete. The final irrigation events were applied through the linear move to only the high water treatments (6.4 cm total water on three dates).

Soil moisture levels were monitored in every plot using a neutron probe at a minimum of weekly intervals (2 access tubes per plot). Additionally, two plots were heavily instrumented with TDR probes in 4 locations at 4 depths (5, 10, 15 and 20 cm). The probes were used to determine the soil surface moisture content at hourly intervals using an automated data acquisition system. In the later part of the season, stem flow gages were added to these plots to measure the cotton's daily transpiration rate. The plants were sampled for nitrate status weekly and the soil nitrogen content was measured at a minimum of monthly intervals. On a weekly basis, plant samples were collected to determine leaf area index (LAI), leaf, stem, and boll dry weights, plant height and percent canopy cover. Canopy level reflectance measurements (blue, 460 nm; green, 559 nm; red, 660nm; red-edge, 710 nm; near-infrared, 810 and 830 nm; and short-wave infrared, 1650nm) and infrared thermometer data were taken 3 times per week over each plot using a hand-held radiometer. Images from a multi-band sensor collected in a coincident experiment provided another source of remotely sensed data for the project (see Moran et. al., "MAC-ATLAS: Verification and validation of a NASA airborne scanner for farm management applications" in this report). Meteorological observations (air temperature, humidity, wind speed, solar radiation, soil temperature, and rainfall) were also recorded.

FINDINGS: At the time of this report, data collection has just been completed for the 1998 cotton-growing season; therefore, only very preliminary results are available. Data from the hand-held radiometer confirmed the sensitivity of reflectance in the visible and near-infrared portion of the

spectrum to crop nitrogen levels found by other researchers (e.g., Bausch and Duke, 1996). For example, figure 2 shows data from the hand-held radiometer collected on 02 October. The data represent treatment averages and are shown as the percent difference from the values measured over the control plots. The average surface temperature or percent reflectance for the control is shown as the line plot, with the values represented on the right hand y-axis. The reflectance is higher than the control for the low nitrogen treatments in the visible portion of the spectrum (460 - 710 nm). These differences are probably a combination of changes in leaf pigment concentration and a reduction in total biomass in the low nitrogen plots, as the low nitrogen plots had a LAI of 2.8 compared to the control LAI of 4.5. The lower leaf area increased the visibility of the soil background that was brighter than the plant material in the visible part of the spectrum. The reduction of leaf chlorophyll levels that are typically associated with nitrogen stress also resulted in an increase in reflectance in the visible spectrum. Therefore, there could be difficulties in discriminating a nitrogen stress response from a general decrease in plant biomass when relying only on remotely sensed data. By developing links between the remotely sensed data and a simulation model, there will be additional information available to determine when these spectral responses could be attributed to other stress conditions.

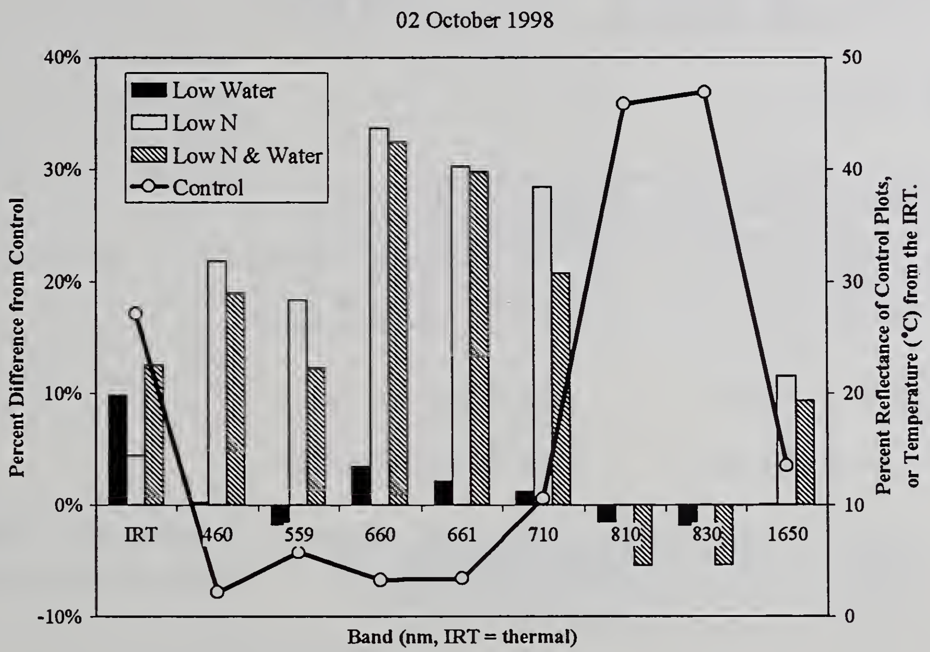


Figure 2. Data collected with a hand-held radiometer on October 2 averaged by treatment. The left-hand y-axis represents the percent difference of the treatment average surface temperature (IRT) or reflectance from the control while the right-hand y-axis represents the actual average readings over the control plots.

There was no clear response in the reflective part of the spectrum associated with the low water treatment, even at 1650 nm that has been correlated with leaf-water content by other researchers (e.g., Grant, 1987). These treatments did have average surface temperatures that were higher than the control (figure 2). However, plot to plot differences in surface temperature were not always consistent in terms of water treatments. Figure 3 is a representation of the individual IRT measurements within each plot from a geographic information system (GIS). For the plots on the south end of the field, the measured surface temperature was greater than the mean of field measurements for the low water plots and less than the mean for the control plots, as expected. However, the north end of the field had a less consistent pattern. For example, plots 3 and 5 both

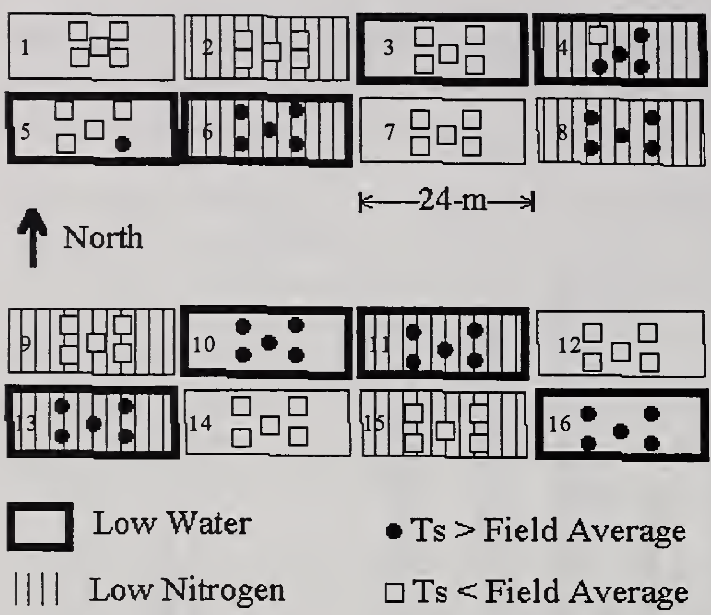


Figure 3. Surface temperature (Ts) measured on October 2nd relative to the field average, shown over the measurement location within the plot.

received low water treatments, but the surface temperatures measured in these plots were lower than the field average. In plot 8, an opposite scenario arose, as this was a high water treatment but the surface temperature was higher than the field average. The plants in plot 8 were unintentionally water stressed earlier in the season, which may provide part of the explanation why this plot did not follow expected trends. Hopefully, after all of the data (soil properties, growth data, plant nitrogen levels) are integrated into the GIS, some explanation for the inconsistencies in plots 5 and 3 can be determined.

INTERPRETATION: The system under development will provide farmers and agricultural consultants with a simple, cost effective data source to map spatial variations in crop water and nitrogen levels. These data will have the potential to serve as an integral part of a decision support system for precision crop management.

FUTURE PLANS: Field experiments similar to the one conducted during 1998 will be repeated for barley during the 1998-99 growing season to determine the issues involved in applying the system to different crops. A carriage system for the linear move irrigation equipment will be mounted during the barley experiment. A second cotton experiment will be conducted in 1999 for validation purposes.

COOPERATORS: Peter Waller and Chris Choi, University of Arizona, Tucson; Robert Lascano, Texas A&M University, Lubbock; Jack Slater, INEEL, Idaho Falls; Jim Phene, Valmont Industries, Valley, NB; Jim Stubbs, CDS Ag Industries, CA.

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QUANTITATIVE REMOTE SENSING APPROACHES FOR MONITORING AND MANAGING AGRICULTURAL RESOURCES

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QUANTITATIVE REMOTE SENSING APPROACHES FOR MONITORING AND MANAGING AGRICULTURAL RESOURCES

MISSION

The ultimate goal of this research is to use remote sensing technology to increase our understanding of processes associated with environmental variability and to provide resource managers with information that will assist them in making tactical and strategic management decisions on farms, rangelands, and natural plant communities. Emphasis will be given to approaches that have potential for operational application, and that also have a strong physical foundation based on quantitative measurements.

SOIL MOISTURE EVALUATION USING SYNTHETIC APERTURE RADAR (SAR) AND OPTICAL REMOTE SENSING IN SEMIARID RANGELAND

M.S. Moran and J. Qi, Physical Scientists

PROBLEM: There is evidence that satellite-based Synthetic Aperture Radar (SAR) sensors could provide a regional assessment of surface soil moisture content (θ_s). Theoretically, SAR backscatter($\sigma°$, dB) detected by orbiting satellite-based sensors (e.g., ERS-2 SAR) is directly related to θ_s; in practice, $\sigma°$ is also highly influenced by topographic features, vegetation density, and variations in small-scale surface roughness. Thus, it is difficult to convert SAR images directly into maps of regional θ_s for heterogeneous terrain. Previous studies have suggested that the accuracy of SAR-based θ_s estimates could be improved by combining data from optical sensors (e.g., surface reflectance and temperature) to discriminate the SAR signal response to vegetation. The objectives of this work were to investigate the sensitivity of ERS-2 C-band SAR backscatter measurements to surface soil moisture content, and to test an approach based on optical (Landsat TM) and radar (ERS-2 SAR) measurements to improve regional estimates of surface soil moisture content.

APPROACH: In this project, we designed an experiment to study the link between ERS-2 SAR C-band backscatter and soil moisture, while minimizing the influence of other conditions. That is, we focused our study on flat, uniformly-vegetated sites and planned to monitor the variations in soil moisture and vegetation cover over time. The sites were named by the dominant vegetation type: Tobosa (*Hilaria mutica*), Sacaton (*Sporobolus wrightii*) and Creosote (*Larrea tridentata*). By choosing flat sites, we avoided the effects of topography; and by monitoring the sites over time (rather than multiple sites over space), we minimized the influence of variations in small-scale roughness conditions. Furthermore, by measuring vegetation density on a monthly basis at each site, we were able to quantify changes in vegetation that might influence SAR $\sigma°$. We requested 8 ERS-2 SAR scenes covering our study site throughout 1997. The dates of these overpasses were selected to correspond closely with the dates of overpasses of the Landsat-5 satellite (Table 1). During each ERS-2 overpass, we visited all three sites and made 49 gravimetric measurements of soil moisture content to 5cm depth over a target area of 90 x 90 m within the larger uniform area of 300 x 300 m.

Figure 1 is a graphic illustration of the basic approach for the use of SAR/optical synergism for estimation of soil moisture content. The effects of soil roughness were taken into account by taking the difference between the SAR backscatter from a given image and the backscatter from a "dry season" image ($\sigma°$-$\sigma°_{dry}$). The vegetation influence was corrected by using an empirical relationship between ($\sigma°$- $\sigma°_{dry}$) and green leaf area index (GLAI), where the latter was derived from the optical data. Thus, the soil moisture conditions are related to the length of the vertical arrow in Figure 1, where the soil moisture content of B is greatest and A least, with C intermediate.

Table 1. Volumetric soil moisture content (%) at three sites in Upper San Pedro River Basin, Arizona.				
Date	**Volumetric Soil Moisture (m^3/m^3)**			**Notes**
	Sacaton	**Creosote**	**Tobosa**	
1/12/97	28.2±5.1	9.0±1.4	19.3±6.1	Soil conditions at all three sites (and throughout the region) were near field capacity due to snowmelt.
2/26/97	13.2±5.7	3.4±0.9	8.0±3.8	Rains in February resulted in moist soil.
3/23/97	7.3±4.3	1.1±0.8	3.7±1.1	There was minimal rain in March and April, and the soil conditions were moderately dry.
4/21/97	5.9±2.2	1.2±0.8	3.1±1.5	
6/1/97	3.5±1.3	0.9±0.2	3.3±1.1	During the hot months of June and July, soil at all sites was very dry and grass was brown.
7/6/97	3.1±1.1	0.7±0.2	2.2±0.6	
8/1/97	27.6±7.3	8.7±1.7	13.1±7.5	Rains in August resulted in high soil moisture and peak vegetation greenness.
9/14/97	13.8±5.0	3.8±1.1	7.0±2.6	A small storm preceeded the September overpass.

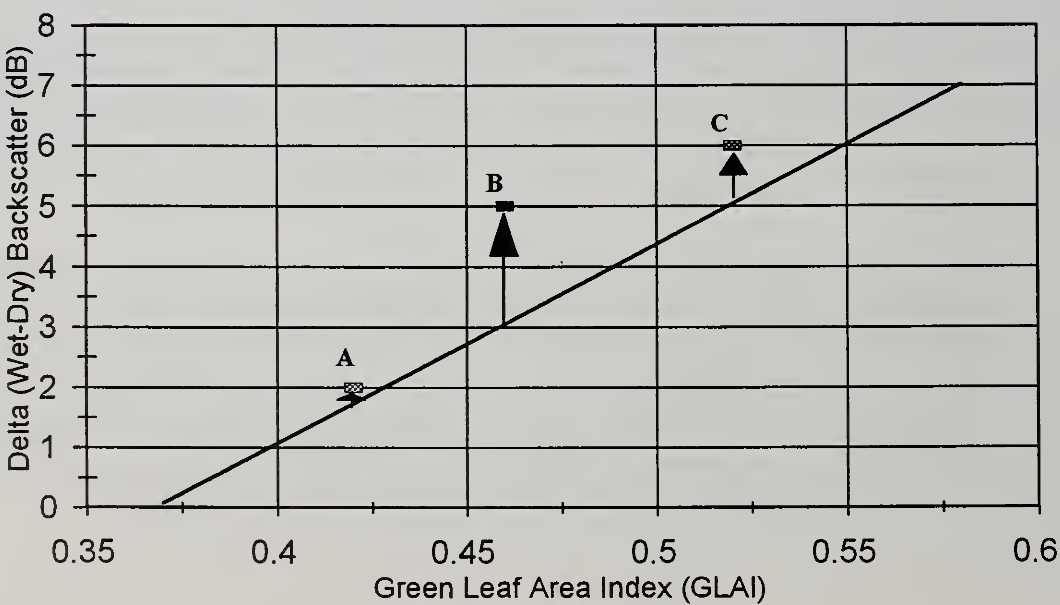

Figure 1. A graphic illustration of the SAR/optical approach for evaluating surface soil moisture developed by Sano (1997). The vertical distance of points A-C from the solid line is related directly to soil moisture content.

FINDINGS: Due to fortunate weather conditions, we obtained a wide range of soil moisture conditions for our study (Table 1). During the June SAR overpass, the soil moisture conditions at all sites were extremely dry, and the late summer greenup of the vegetation had not yet occurred. Consequently, we designated it as the "dry" scene and subtracted the June SAR backscatter (σ^o_{dry}) from the backscatter measured on the January, February and March dates to account for the contribution of surface roughness to the SAR signal.

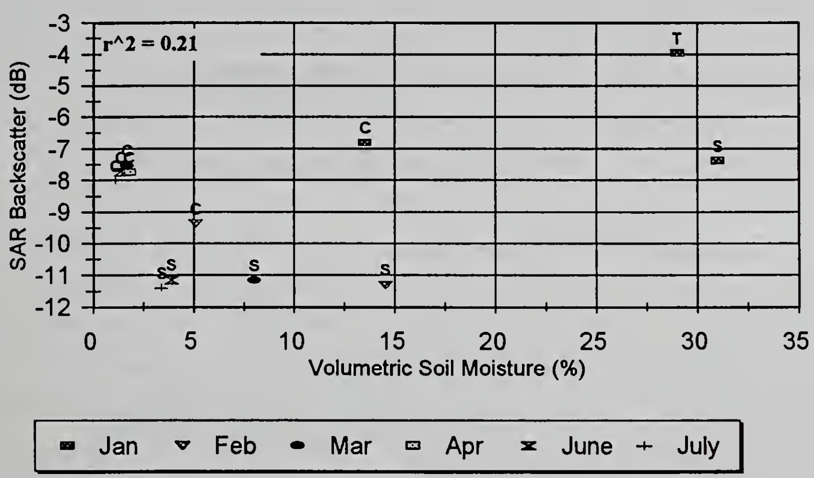

Figure 2. The relation between C-band SAR backscatter and surface (5cm) soil moisture content for three sites [labeled S (Sacaton), C (Creosote) and T (Tobosa)] and four dates in January, February, March and June.

Results showed that measured C-band SAR backscatter (σ^o, dB) was poorly correlated (r^2=0.45) with surface soil moisture content (θ_s) at the three field sites (Figure 2). However, when the data were corrected for differences in surface roughness and standing brown vegetation biomass (based on Figure 1), there was a good correlation (r^2=0.70) between (σ^o - σ^o_{dry}) and θ_s (Figure 3). Regional maps of surface volumetric soil moisture obtained from the January and March SAR and TM images show a good contrast between regional soil moisture conditions (Fig. 4).

INTERPRETATION: These preliminary results were encouraging, though not entirely conclusive. Despite the good relation between SAR backscatter (σ^o-σ^o_{dry}) and θ_s, the overall sensitivity of the SAR signal to changes in soil moisture was low. For the Sacaton site, a change in soil moisture of 25% resulted in a change in σ^o-σ^o_{dry} of only 3 dB. This is notable since 25% is the maximum soil moisture range expected for sandy loam soils in Arizona's semiarid rangeland.

FUTURE PLANS: This approach is useful for mapping spatially distributed soil moisture patterns within 5 cm of the surface. Unfortunately, many hydrologic applications require vadose zone soil moisture measurements rather than surface soil moisture. By combining SAR-derived surfaces soil moisture maps with a soil-vegetation-atmosphere transfer (SVAT) model, it may be possible to obtain spatially distributed, temporally continuous information on vadose zone soil moisture. Preliminary analysis of the simultaneous heat and water (SHAW) SVAT model showed that this approach has potential for providing a better understanding of changes in natural land surfaces.

COOPERATORS: Daniel C. Hymer, NASA Goddard Space Flight Center; Edson E. Sano, EMBRAPA/CPAC, Brazil

REFERENCES: Sano, E.E. (1997). Sensitivity analysis of C- and Ku-band Synthetic Aperture RADAR data to soil moisture content in a semi-arid region. Ph.D. Diss., UA. Dept. SWES.

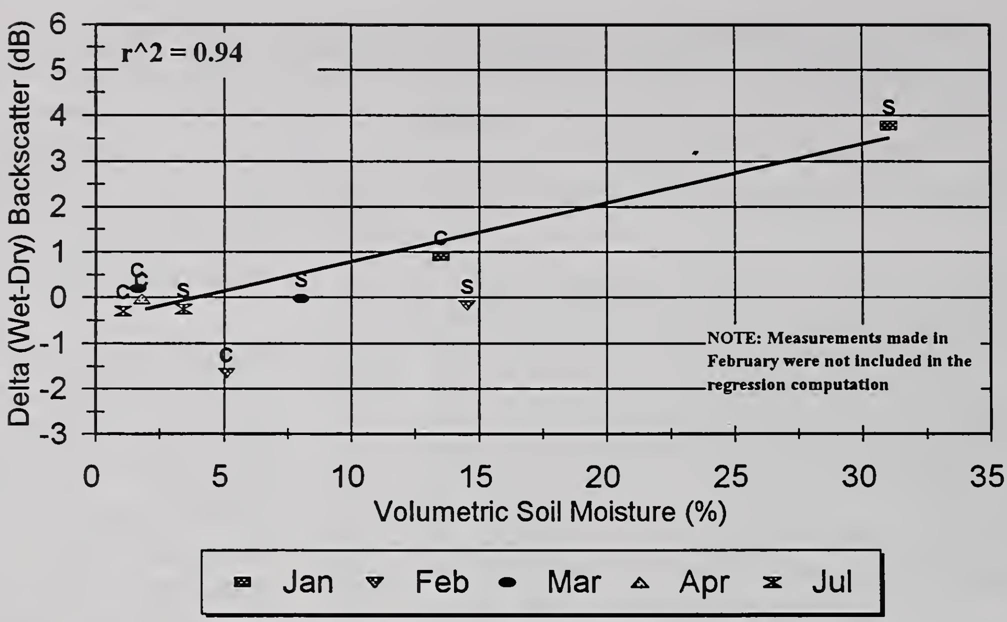

Figure 3. Same as Figure 2, except the SAR backscatter was normalized for differences in surface roughness by subtracting the June SAR backscatter signal from the backscatter signal of the other dates. Note the Tobosa site was not covered by most images.

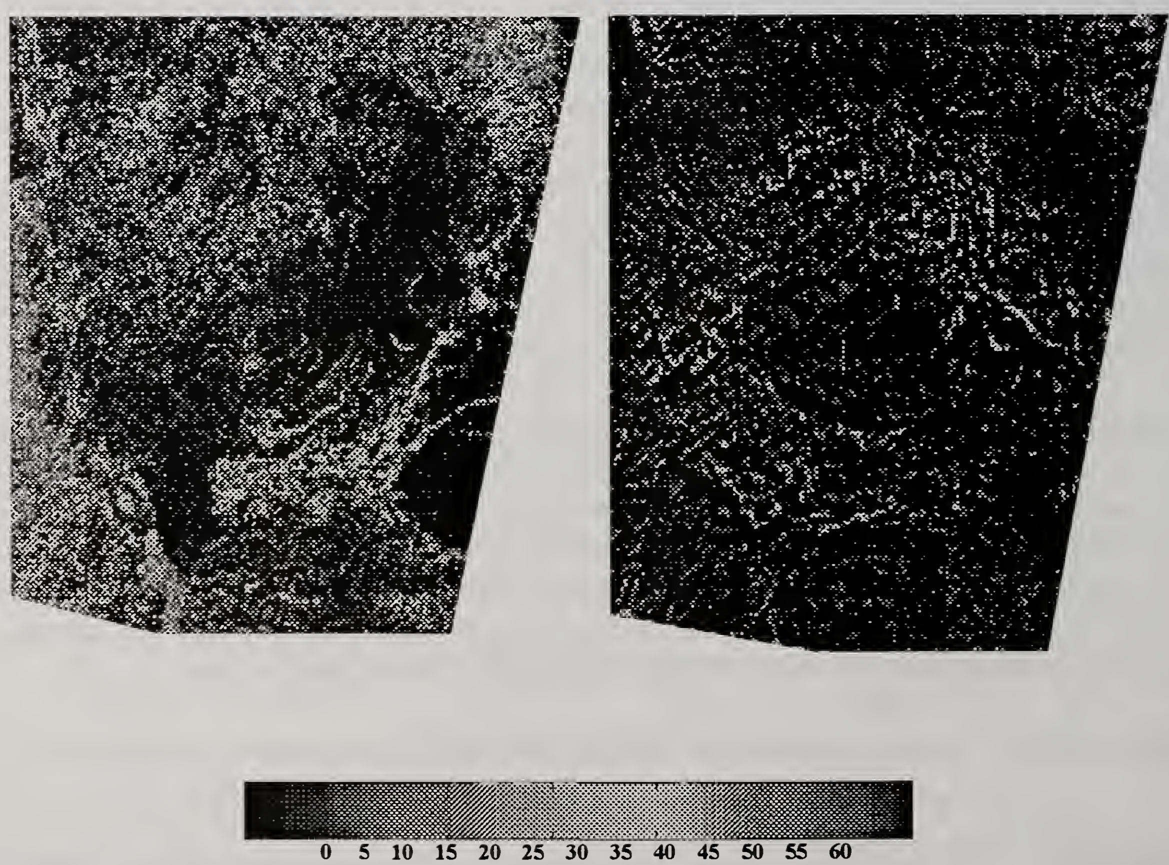

Figure 4. Images of volumetric soil moisture (%) for the Upper San Pedro Basin on January 12 (left) and March 23 (right) 1997, derived from the relation between SAR backscatter (σ^o-σ^o_{dry}) and θ_s (Fig. 3).

RADAR IMAGERY FOR PRECISION CROP AND SOIL MANAGEMENT

M.S. Moran and J. Qi, Physical Scientists

PROBLEM: Studies over the past 25 years have shown that measurements of surface reflectance and temperature (termed optical remote sensing) are useful for monitoring crop and soil conditions. Far less attention has been given to the use of radar imagery, even though Synthetic Aperture Radar (SAR) systems have the advantages of cloud penetration, all-weather coverage, high spatial resolution, day/night acquisitions, and signal independence of the solar illumination angle. The greatest weakness of SAR data for precision farming is the poor understanding of the response of SAR σ^o to agricultural soil and plant conditions.

APPROACH: In the study presented here, we attempted to capitalize on the good understanding of the response of the optical data to plant/soil conditions in order to interpret SAR images of an agricultural region. For five dates in 1995 through 1997, we acquired pairs of images from the Landsat TM sensor and the ERS-2 SAR sensor covering the University of Arizona Maricopa Agricultural Center in central Arizona (e.g., Fig. 1). The information obtained from multispectral reflectance (ρ) and temperature (T_s) measurements made with the TM sensor was used to interpret the backscatter signal (σ^o) received by the ERS-2 C-band SAR sensor. In particular, we focused on the determination of within-field variations in

- soil roughness (related to tillage, subsidence or erosion);
- vegetation density (related to seeding, crop vigor and pest infestations); and
- surface soil moisture condition (related to monitoring irrigation efficacy, soil texture).

Theoretically, there is a relation between the optical and SAR sensitivities to variations in soil surface roughness, vegetation cover, and soil moisture (Table 1).

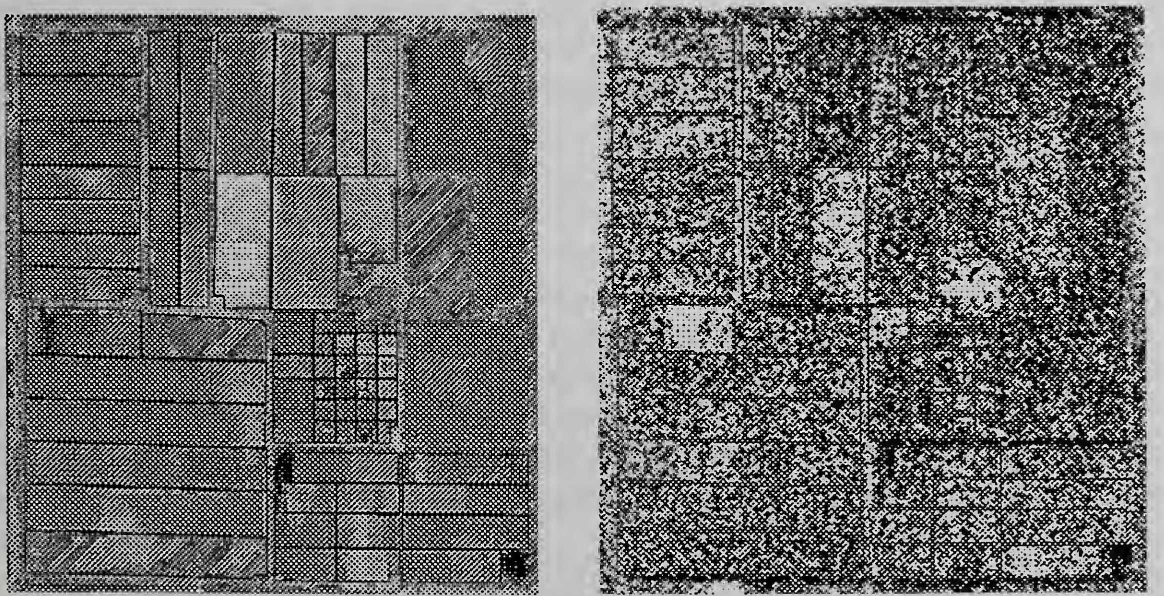

Figure 1. Images of Landsat TM reflectance (left) and ERS-2 SAR backscatter (right) covering Maricopa Agricultural Center acquired on 21 May and 19 May 1997, respectively. The vector overlay designates the MAC field borders, and the total area covers 770 hectares.

Table 1. Theoretical response of optical and SAR measurements to changes in plant/soil condition, where ↑ indicates an increase, ↓ indicates a decrease, and – indicates no substantial change. σ^o is backscatter, T_s is surface temperature, ρ_{Red} and ρ_{NIR} are surface reflectance in the Red and NIR spectrum, and SAVI is the soil adjusted vegetation index (SAVI = $(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{NIR})$, which is linearly related to percent vegetation cover.

Change in Plant/Soil Condition	σ^o	T_s	ρ_{Red}	ρ_{NIR}	SAVI
Increase in surface roughness	↑	–	↓	↓	–
Decrease in vegetation biomass	↑	↑	↑	↓	↓
Increase in surface soil moisture content	↑	↓	↓	↓	–

For analysis of the SAR information, we defined a set of normalized difference (Δ_N) indices, where

$$\Delta_N\sigma^o = (\sigma^o_1 - \sigma^o_2)/(\sigma^o_X - \sigma^o_M), \tag{1}$$
$$\Delta_N T_s = (T_{s1} - T_{s2})/(T_{sX} - T_{sM}), \tag{2}$$
$$\Delta_N\rho_{Red} = (\rho_{Red1} - \rho_{Red2})/(\rho_{RedX} - \rho_{RedM}), \tag{3}$$
$$\Delta_N\rho_{NIR} = (\rho_{NIR1} - \rho_{NIR2})/(\rho_{NIRX} - \rho_{NIRM}), \tag{4}$$
$$\Delta_N SAVI = (SAVI_1 - SAVI_2)/(SAVI_X - SAVI_M), \tag{5}$$

and the subscripts 1 and 2 refer to two locations within the field, and subscripts X and M refer to the maximum and minimum values within the entire farm. These indices range from -1 to 1, and are indicative of the optical and SAR responses to changes in plant/soil condition.

For this preliminary analysis, we selected all MAC fields in the four 1995/1996 images that had a record of distinctive within-field differences in tillage, soil moisture, and vegetation density. Since results were similar for fields of similar surface conditions, three fields were selected as examples for illustration here. According to field notes and on-site observations, Field 1 was fallow, but part of the field had been laser leveled and part was still rough due to cultivation; Field 2 was planted with alfalfa, but half of the field had been recently harvested, and Field 3 was also fallow, but part of the field had been flood irrigated.

FINDINGS: All three fields (numbered 1-3 for reference herein) had a notable increase in the SAR σ^o ($\Delta_N\sigma^o \sim 0.2$) from one end of the field to the other (Figures 2 and 3). The increase in $\Delta_N\sigma^o$ in Field 1 was due to the increased scattering of the SAR signal due to soil roughness. In Field 2, the increase in $\Delta_N\sigma^o$ resulted from a decrease in the alfalfa crop density due to a recent harvest. In Field 3, $\Delta_N\sigma^o$ increased due to the change in soil moisture and the sensitivity of the SAR signal to the dielectric constant of the surface. The dielectric constant of water is about 80 (in the C-band wavelength) and that of dry vegetation or soil is about 2-3.

The visual and quantitative assessment presented in Figures 2 and 3 showed that the response of the optical data to the three different field conditions corresponded well with the theoretical hypotheses

presented in Table 1. In Field 1, as the soil roughness increased, $\Delta_N\rho_{NIR}$ and $\Delta_N\rho_{Red}$ decreased by 0.2 due to increased surface shadows, and $\Delta_N T_s$ and Δ_NSAVI remained near zero for the two roughnesses. In Field 2, as the vegetation decreased due to harvest, $\Delta_N T_s$ increased by about 0.2 due to the decrease in transpiration, $\Delta_N\rho_{NIR}$ decreased by 0.5 and $\Delta_N\rho_{Red}$ increased by 0.4 due to the decrease in leaf area and photosynthetic activity, causing a decrease in Δ_NSAVI of 0.62. In Field 3, as the soil moisture increased, $\Delta_N T_s$ decreased by about 0.5 due to evaporative cooling, $\Delta_N\rho_{NIR}$ and $\Delta_N\rho_{Red}$ decreased by 0.1 and 0.2 respectively due to water absorption, and Δ_NSAVI remained near zero.

Based on data for fields not illustrated in Figures 2 and 3, we found that the optical data were also useful for discriminating "mixes" of effects of roughness, vegetation and soil moisture. For example, in the SAR image acquired in November 1995, two adjacent fields of alfalfa showed no difference in SAR σ^o ($\Delta_N\sigma^o$~0). Yet, we computed large negative values of $\Delta_N T_s$ and Δ_NSAVI. Based on the optical response, we postulated that one of the fields was recently harvested and had a low soil moisture content; the other was near full vegetation cover and had been recently irrigated. As a result, the high σ^o associated with low crop cover was offset by the low σ^o associated with high soil moisture content, and $\Delta_N\sigma^o$~0.

INTERPRETATION: Overall, the Δ_N indices worked well to discriminate the causal relation between surface conditions and SAR σ^o. Though results for only three fields are illustrated here, similar results for several more fields showed that this method has potential for interpretation of SAR imagery with coincident optical imagery. These results also illustrated the sensitivity of Landsat TM and ERS-2 SAR imagery to differences in tillage, surface soil moisture, and vegetation density.

FUTURE PLANS: Future work on this data set will be focused on compiling the SAR, optical and field information necessary to develop a relation to facilitate interpretation of the SAR image, which may take the form

$$\Delta_N\sigma = a + b\Delta_N T_s + c\Delta_N\rho_{NIR} + d\Delta_N\rho_{Red} + e\Delta_N\mathrm{SAVI}, \tag{6}$$

where the parameters *a-e* are empirical coefficients determined by multiple regression analysis. Recognizing the limitations of optical remote sensing data due to cloud interference and atmospheric attenuation, the findings of this study should encourage further studies of SAR imagery for crop and soil assessment.

COOPERATORS: Daniel C. Hymer, NASA Goddard Space Flight Center, Maryland; Yann Kerr, Centre d'Etudes Spatiales de la Biosphere (CESBIO), Toulouse, France.

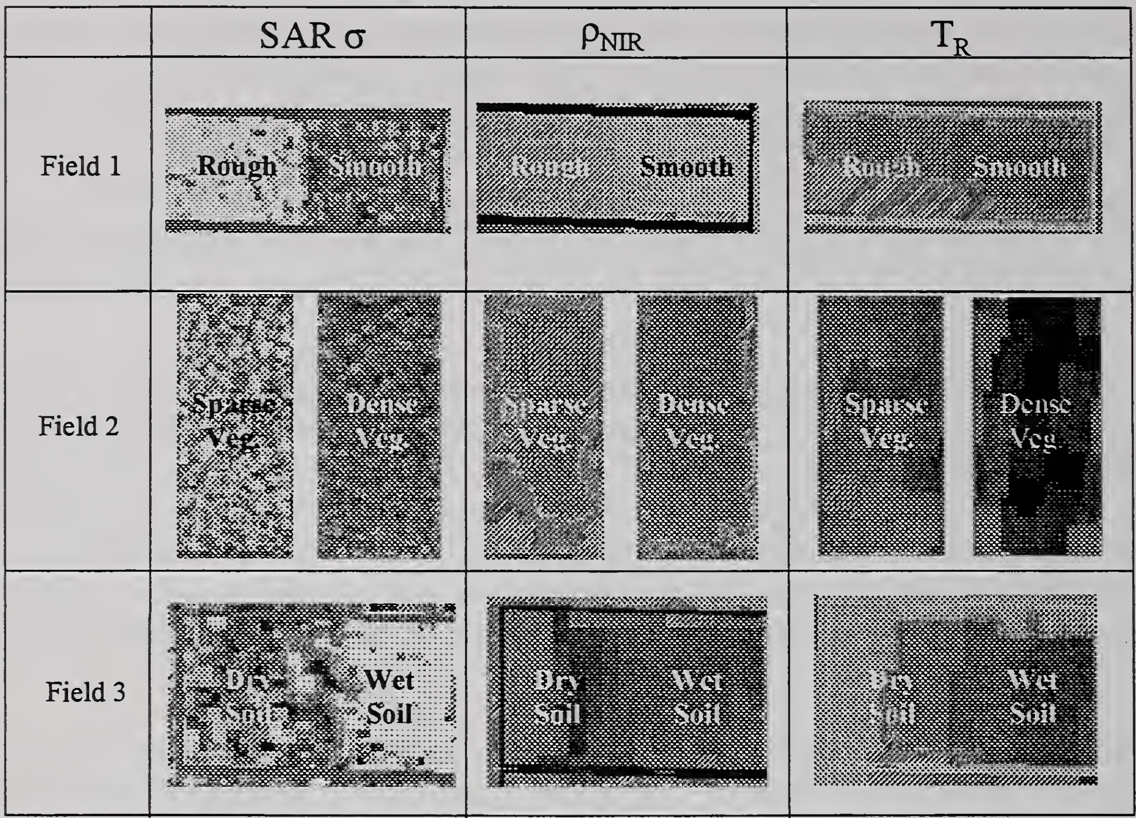

Figure 2. Extracts of SAR and optical data for the three study fields, illustrating the differences in spectral response in SAR backscatter (σ), NIR reflectance (ρ_{NIR}), and radiometric surface temperature (T_r) to variations in field tillage, vegetation density, and surface soil moisture.

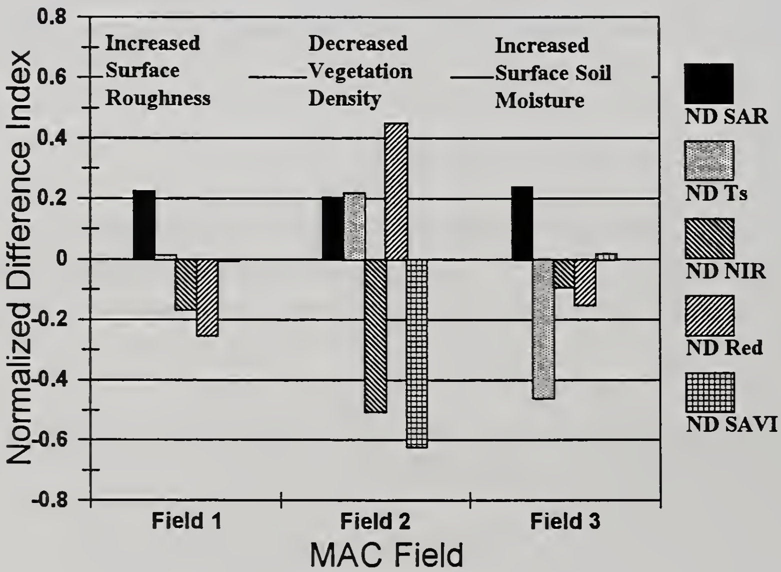

Figure 3. The response of Δ_N indices (Eqs. 1-5) to variations in field roughness, vegetation density and surface soil moisture. The five legend captions refer to $\Delta_N\sigma^o$, $\Delta_N T_s$, $\Delta_N\rho_{Red}$, $\Delta_N\rho_{NIR}$, and Δ_NSAVI, respectively.

PREDICTING CARBON ACCUMULATION IN WHEAT

P.J. Pinter, Jr., Research Biologist; T.J. Brooks, Research Technician; B.A. Kimball, Supervisory Soil Scientist; G.W. Wall, Plant Physiologist; E.M. Barnes, Agricultural Engineer

PROBLEM: Remote sensing technology, coupled with an expanding network of satellites, has made it possible to monitor the condition of the planet's natural and agricultural resources on a regular basis. Mechanistic approaches for using satellite-derived vegetation indices to estimate net primary productivity (NPP) are currently the focus of intensive scientific effort. In the simplest approach, a normalized difference vegetation index (NDVI) is used to estimate the fraction of absorbed photosynthetically active radiation (fAPAR, 400 to 700 nm) captured by plants for potential use in photosynthesis. This is multiplied by the incident solar PAR and also by the efficiency with which solar energy is converted into plant biomass (e.g. RUE, radiation use efficiency, g MJ-1). When accumulated on a daily time step (t), this yields NPP in terms of grams of carbon or biomass m-2 per unit time:

$$NPP = \sum_{t=0}^{n} [fAPARt * PARt * RUE] \qquad \text{[eqn. 1]}$$

Validating such an approach for complex ecosystems on a regional or global scale is a difficult if not impossible task for a number of practical and theoretical reasons. However, agricultural monocultures offer potentially simpler systems for testing the validity of remote NPP predictive methods. During the Free Air Carbon dioxide Enrichment (FACE) wheat project, we measured NDVI regularly using ground based radiometers, developed ways to estimate fAPAR from NDVI, and evaluated RUE with canopy gas exchange chambers. This is a preliminary report outlining our use of these parameter to estimate NPP for wheat.

APPROACH: Spring wheat (*Triticum aestivum* L. cv Yecora Rojo) was grown for 4 years under ambient (Control, ~370 mmol mol-1) and elevated (nominal +200 mmol mol-1) levels of CO_2 in the FACE facility located on The University of Arizona Maricopa Agricultural Center (MAC). During the first 2 years (1993-94 and 1994-95), main CO_2 treatment plots were fertilized at optimum rates but split in half to test the effect of either a wet or a dry irrigation regime on wheat response to CO_2. In years 3 and 4 (1995-96 and 1996-97), CO_2 treatments were irrigated at optimum rates but split to test high (~275 kg N ha-1) or low (<75 kg N ha-1) nitrogen fertilization regimes. All treatment combinations were replicated 4 times each season. Plants were oriented in east-west rows spaced 0.25 m apart and irrigated using a subsurface drip irrigation system.

Canopy reflectance factors were measured 1 to 5 times a week using a handheld, Exotech radiometer (Exotech, Inc., Gaithersburg, MD) equipped with 15° fov optics. Measurements were made at a 57° solar zenith angle. Red (0.61 to 0.68 mm) and near-infrared (NIR, 0.79 to 0.89 mm) reflectance factors were used to compute the Normalized Difference Vegetation Index:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \qquad \text{[eqn. 2]}$$

Incident (I), transmitted (T), and reflected (R) light in photosynthetically active wavelengths (PAR, 400 to 700 nm) were measured at midday on 16 dates during experiment years 2 and 3 using an Accupar sensor (Decagon Instruments, Inc., Pullman, WA). Measurements were taken above and below the plant canopy along the north edge of the final harvest area. The 80 cm-long sensor was oriented at a 45° angle to the plant rows. Reflected PAR was also obtained over a bare soil plot (RPARs). Then fAPAR was computed using a light balance equation:

$$fAPAR_c = 1 - \left(\frac{TPAR_c}{IPAR}\right) - \left(\frac{RPAR_c}{IPAR}\right) + \left(\frac{TPAR_c}{IPAR}\right) * \left(\frac{RPAR_s}{IPAR}\right) \quad \text{[eqn. 3]}$$

where subscripts c and s refer to wheat canopy and a bare soil plot, respectively. The fAPAR parameter was converted to a "biologically effective" fAPAR by multiplying it by a green canopy fraction (the ratio of green to brown leaf components obtained from weekly plant samples). Absorbed PAR (APAR) was determined as the product of fAPAR and daily values of incident solar PAR (0.45* global solar radiation) from the Arizona Meteorological Station (AZMET) at MAC.

Wheat canopy photosynthesis was measured using an open chamber system measuring 1 by 0.75 by 1.2 m and covering 4 rows of wheat. Ambient air was drawn from towers above the canopy and blown into the chamber through a 0.20 m inlet, where CO_2 was sampled. Air inside the chamber was mixed by two 1/40 hp fans operating at 3000 rpm. Air exited through a 0.15 m diameter outlet and was again sampled. This ensured that the chamber was operated at positive pressure to minimize leakage error and contamination by soil CO_2 flux. Canopy photosynthesis was calculated as:

$$CER = \frac{[(CO_{2in}) - (CO_{2out})] * F}{s} \quad \text{[eqn. 4]}$$

where CER is the Carbon Exchange Rate, CO_2in is the inlet CO_2 concentration, CO_2out is the outlet CO_2 concentration, F is the flow rate through the system, and s is the ground area covered by the chamber (see Brooks et al. pp. 78-81 in the 1997 USWCL Annual Research Report).

FINDINGS: Figure 1 shows that the NDVI derived from canopy reflectance was strongly correlated with the biologically effective fAPAR measured with the Accupar sensor at midday. (Abbreviations in this and following figure legends: C, Control, ambient CO_2; F, FACE, elevated CO_2; W, wet irrigation regime; D, dry irrigation regime; L, low N; H, high N). The data revealed that the fAPAR vs NDVI relationship was independent of year, CO_2, irrigation, or nitrogen treatments. Moreover, a single cubic relationship fit data for pre- and post-anthesis wheat equally well and thus could be used to predict fAPAR for calculating daily APAR throughout the season.

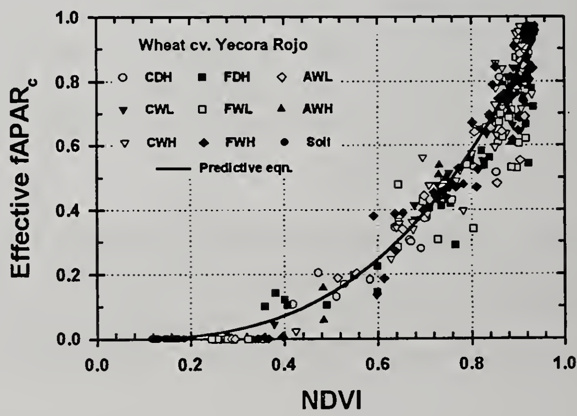

Figure 1. Fractional APAR and NDVI measured during the FACE Experiments in 1994-95 and 96-97.

Gas exchange data obtained using the canopy chambers during the 1996-97 FACE experiment showed that daytime carbon assimilation varied markedly as the season progressed and changes occurred in the amount of photosynthetically active biomass (Fig. 2). Rates were lowest early in the season when plants were small and again late in the season when canopies were senescing. Between booting and early grain fill, peak photosynthetic rates of 15 to almost 20 g C day-1 m-2 were observed in well-watered wheat with adequate supplies of nitrogen. Photosynthetic rates were modulated by CO_2 and nitrogen supplies. Elevated CO2 stimulated daytime carbon assimilation (g C m-2 day-1) by an average of about 19% in the high N fertilizer treatment and by 8% in the low N treatment. When compared with the high N treatment, rates in plants with low N were reduced by an average of 22%.

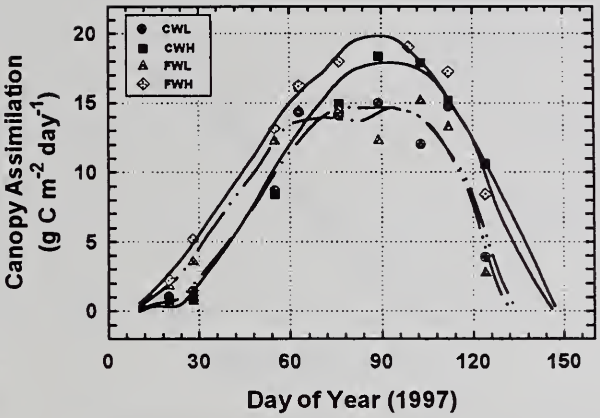

Figure 2. Daytime assimilation of carbon measured with the canopy chambers during the FACE 1996-97 wheat experiment.

Many simple crop models assume a constant RUE when converting APAR into biomass. In reality this parameter is rather dynamic, varying with plant stress, environmental conditions, and possibly stage of growth. To see whether the chamber data displayed RUE differences due to the experimental treatment structure, the assimilation data was graphed versus the amount of PAR captured by the canopy (Fig. 3). The later was estimated as the product of IPAR and NDVI-predicted fAPAR for the same dates and in the same replicate where the chambers were located. We acknowlege considerable scatter in these data and believe much of it is due to experimental error, unidentified plant stresses, and the difficulty of the technique itself. However, for the predictive purposes of this report, we fit separate linear models to data from the ambient and elevated CO_2 treatments. Results are shown in figure 3 as the dotted line for the ambient treatments (CWL and CWH) and as the solid line for the elevated CO_2 treatments (FWL and FWH). The slopes of those lines represent a method for computing RUE. They show ambient treatments yielded 1.68 g C MJ-1 APAR, while the FACE treatments had 8% higher assimilation at 1.81g C MJ-1 APAR.

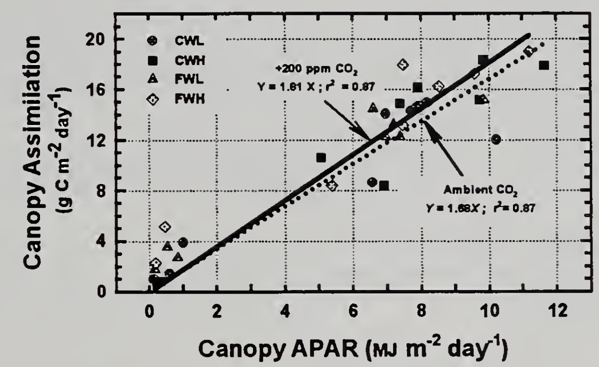

Figure 3. Daytime canopy assimilation versus absorbed PAR during the 1996-97 FACE experiment.

Daily values for NDVI-predicted fAPAR were estimated by linear interpolation and substituted into [eqn. 1] with daily incident PAR from the AZMET station and RUE as determined above. This enabled us to extrapolate the chamber assimilation data to predict carbon accumulation for all treatments and replicates. Results are shown as predictions of cumulative carbon produced throughout the 1996-97 season (Fig. 4) and also as the total carbon produced each month (Fig5).

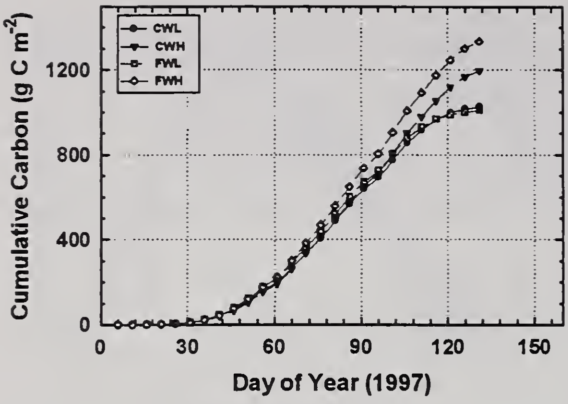

Figure 4. Cumulative carbon predicted by the remote model.

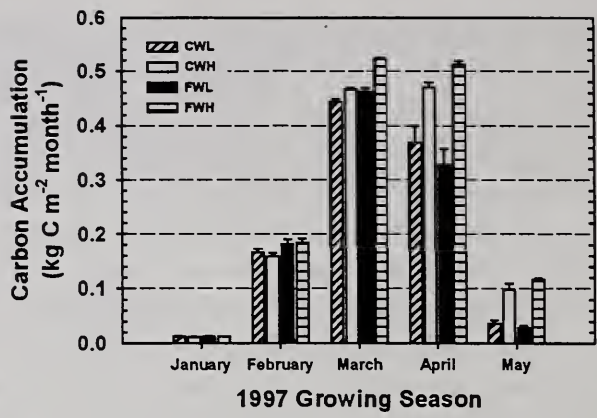

Figure 5. Carbon (mean ± 1 sd) produced each month.

INTERPRETATION: The simple NPP model (eqn.1) is based on a functional relationship between the size of the photosynthetic apparatus and potential carbohydrate production under optimum conditions. Our results showing a good correlation between NDVI-predicted APAR and assimilation rates obtained using the canopy gas exchange chambers were very encouraging. That finding alone provides a compelling argument for using a multispectral surrogate (i.e. NDVI) to estimate PAR captured by the wheat canopy. Initial comparisons between predicted and observed biomass revealed that the simulated trends during the season were realistic and preserved the relative rankings between treatments. In the model, NDVI automatically compensates for antecedent cultural and growth conditions, chronic plant stresses like drought, and physiological responses to end-of-season senescence. Acute plant stresses such as short term water stress could be handled by modifying RUE with a thermal index like the Crop Water Stress Index which is related to plant water status.

FUTURE PLANS: On an absolute basis, the NPP model overpredicted measured values by about one third. We believe that most of this discrepancy was due to parameters that have not yet been properly accounted for in the comparison (e.g. root biomass and exudates, night time respiration, losses due to herbivory, sampling inefficiencies, etc.) Thus, work during the coming year will address this apparent disparity. We will then apply the model to earlier FACE wheat datasets and determine overall performance. We also plan to evaluate NDVI estimates of NPP as potential feedback mechanisms to make periodic adjustments to predictions from crop growth models (see Barnes et. al. "Integration of remote sensing and crop growth models to provide decision support for precision crop mananagement" in this volume).

COOPERATORS: Collaborators include G. Wechsung, Humbolt University, Germany; F. Wechsung and T. Kartschall, Potsdam Institute for Climate Research, Potsdam, Germany; A. Matthias, S. Leavitt, and T. Thompson from The University of Arizona; R. Rauschkolb (deceased), B. Roth, and P. Murphree from MAC; and K. Lewin, J. Nagy, and G. Hendrey from Brookhaven National Laboratory. We also wish to thank R. Rokey, S. Gerszewski, and the FACE plant sampling crew for technical assistance in the field. See Kimball et al. "Progress and Plans for the FACE Project" in the 1997 USWCL Annual Research Report for a more complete listing of cooperators.

GERMPLASM IMPROVEMENT AND AGRONOMIC DEVELOPMENT OF NEW ALTERNATIVE INDUSTRIAL CROPS

CONTENTS

GERMPLASM IMPROVEMENT AND AGRONOMIC DEVELOPMENT OF NEW ALTERNATIVE INDUSTRIAL CROPS

MISSION

To acquire and characterize germplasm of guayule, lesquerella, vernonia, and other promising new, alternative crops. To evaluate and enhance germplasm of new crops for industrial raw materials. To develop knowledge of floral biology and seed production and plant responses to stresses. To develop economical, cultural and seed production systems for new crops under various conditions. To develop methods for efficient guayule latex extraction and seed oil analyses for characterizing latex, resin, and oil properties.

GUAYULE LATEX, RUBBER, AND RESIN

F.S. Nakayama, Research Chemist; T.A. Coffelt and D.A. Dierig, Research Geneticists;
S.H. Vinyard and K.D. Eggemeyer, Research Technicians

PROBLEM: Post-harvest handling of guayule shrubs prior to the extraction of latex rubber is an important aspect in the culture of this arid-adapted crop. The integrity of the latex must be maintained to avoid loss of latex and degradation of its quality. A standard reliable method for latex determination is required that can be used by all researchers in the breeding, agronomy and processing areas. The total rubber content of shrubs is known to vary with the season, but no information is available on the amount of rubber latex that can be extracted as a function of time of year. Such information is valuable for scheduling shrub harvest throughout the year. Finding uses for the waste bagasse material resulting from latex extraction is essential to improve the economics of guayule commercialization.

APPROACH: For latex analysis, the mechanics of the blender grinding method was investigated because the various types of blenders available commercially have different grinding characteristics. This involved grinding samples at different time intervals. In addition, the latex stabilities of the homogenates were established because the latex analysis of the blended samples could not be done at the same time.

The effect of guayule shrub storage on latex extractability of was determined. Storage treatments consisted of natural drying, shading, and shading with added moisture to maintain the water content of the harvested shrub. The stored shrubs were kept moist by placing them in burlap bags and wetting them two to three times a day. In addition, the handling of the shrub from the time it was ground to the time when the actual extraction of the latex was made was studied as part of the post-harvest handling of the shrub. The freshly ground shrub was treated as soon as practical with the antioxidant-pH adjusted medium used for latex extraction. A garden-type chipper was modified so that the chipped plant material could be fed directly into the extraction solution to minimize exposure of the comminuted material to the atmosphere. Four varieties of guayule were harvested on a bimonthly basis to determine the effect of harvest time on latex yields.

For the potential utilization of the waste bagasse after latex extraction from the whole shrub, bagasse and whole-plant materials were sent to various ARS and State Experiment Station personnel to test for pest control properties of the resin extracts. Bagasse will also be fabricated into wood products and the resin in the bagasse will be used to treat wood.

FINDINGS: Two types of blenders (Oster & Waring) used at the ARS Albany and Phoenix locations gave different results for latex analysis. This was due primarily to the differences in the rpms of the blender blades. By increasing the grinding time of the slower rpm blender, equivalent results were obtained for the two types of blenders. This information is important when analytical results are compared among laboratories to make sure that plant grindings are equivalent. The latex in the homogenates prepared from the blenders could be maintained in the pH-adjusted antioxidant for at

least 100 days when the latex concentration was greater than 5 mg/ml. Thus, this information will permit greater flexibility in the scheduling of latex analysis.

The latex in the stored whole shrub could be maintained for at least two weeks when the shrub was kept moist (Fig. 1). In this case, the field-harvested shrubs were dipped in water and placed in burlap bags for transportation to the laboratory. They were kept under a screen shade and soaked with water two to three times a day for two weeks. Other harvested shrubs were also placed in burlap bags, and one set was left in the sun and the other in the shade. Water was not added to these shrubs. The latex extractability was similar for the shaded and unshaded shrubs with both showing a large decrease in latex extracted.

The decrease in latex extractability was closely related to the water contents (Fig. 2) of the shrub. Note that the water content presented here can exceed 100 % because it is based on the dry weight.

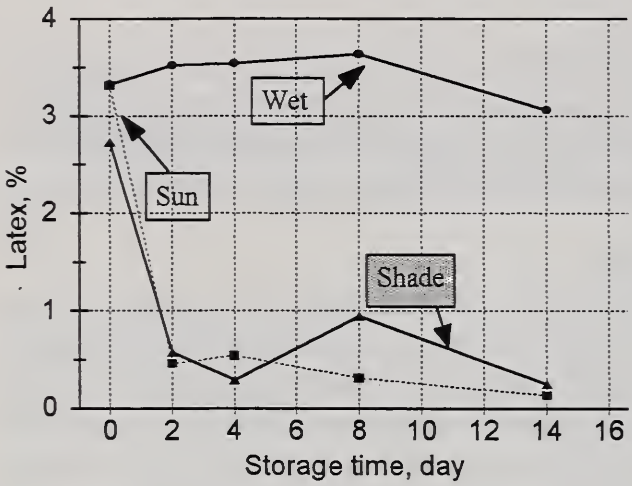

Figure 1. Effect of storage condition on latex extractability from shrub.

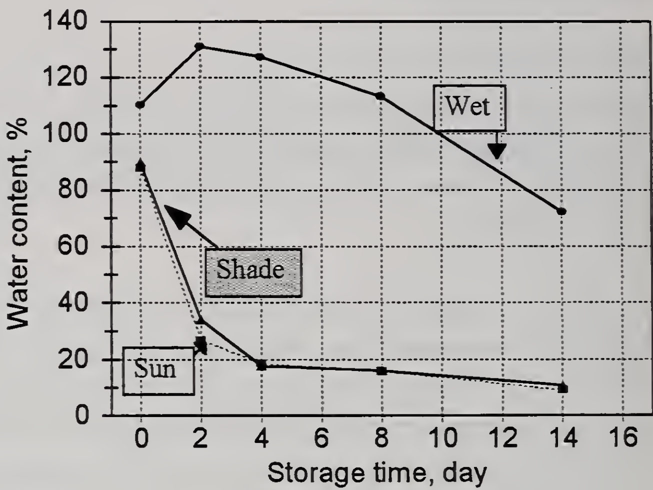

Figure 2. Effect of storage condition on water content of shrub.

Shrub drying below 40% greatly decreased the latex extracted. In contrast, by maintaining the shrub water content above 80%, latex extractability was maintained. The shrub water content between days 8 to 14 had a large decrease, but this was reflected in only a slight drop in latex extractability. The decrease in water content may not have occurred until a few days prior to the sampling. The experiment was conducted in June when the water stress is expected to be large.

The importance of water in plant cells is shown by these results. Dehydration can cause the rubber particles in the cells to coagulate and no longer be in the emulsion state. Thus, it is necessary to keep the plant in a moist condition before the extraction process. For commercial purposes, an adequate coordination between shrub harvest and the latex extraction process must be made to insure that the shrubs do not get dehydrated.

Rubber extraction from the shrub takes place after the shrub is chipped or ground, but not necessarily

immediately following the grinding process. For solid rubber extraction, for example, the ground material is further flaked and stored in silage-type bins before the organic solvent extraction process actually takes place.

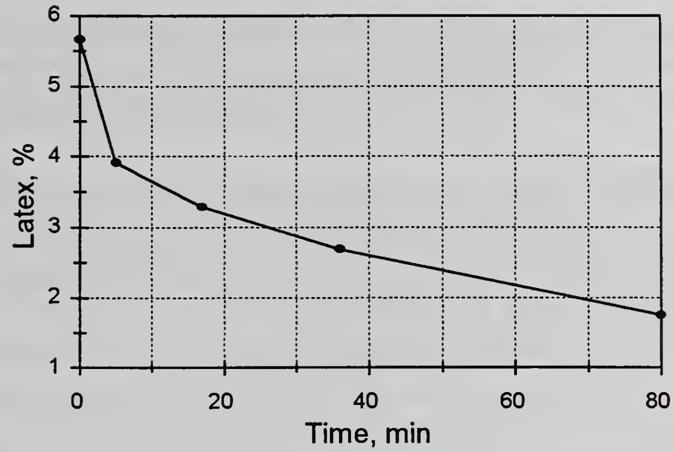

Figure 3. Effect of antioxidant treatment time on latex extraction.

We found with latex rubber that a delay in extracting latex after 'dry' grinding can drastically decrease the amount that can be extracted (Fig. 3). In this example, the chipped shrub was placed into the antioxidant extracting solution at various times after chipping. For the zero time, the shrub was allowed to drop directly into a container with the antioxidant solution so that a minimum interval between chipping and solution treatment was encountered. A time delay as short as 5 min greatly reduced the amount of latex extracted.

For latex analyses of whole plant samples, we have been chipping the shrub directly into the antioxidant solution to avoid this problem of latex loss. Also, if the shrub materials such as branches cannot be analyzed immediately, they are stored under refrigeration in plastic containers.

The latex content of the guayule shrub appeared to follow a seasonal pattern. Bimonthly sampling between March and September showed that the latex contents were lowest over the summer period (Fig. 4). All four lines had a decrease in latex from March to May and then a trend for an increase in September. The shrub size and rate of growth of line 11591 (not included) are usually lower than the other lines, but in this instance the latex per plant was higher than that of others. The G7-11 TC is a tissue culture derivative of G7-11 and both appeared similar in their response to season. The relationship covers only a limited time span, but follows results observed for total rubber content in the plant.

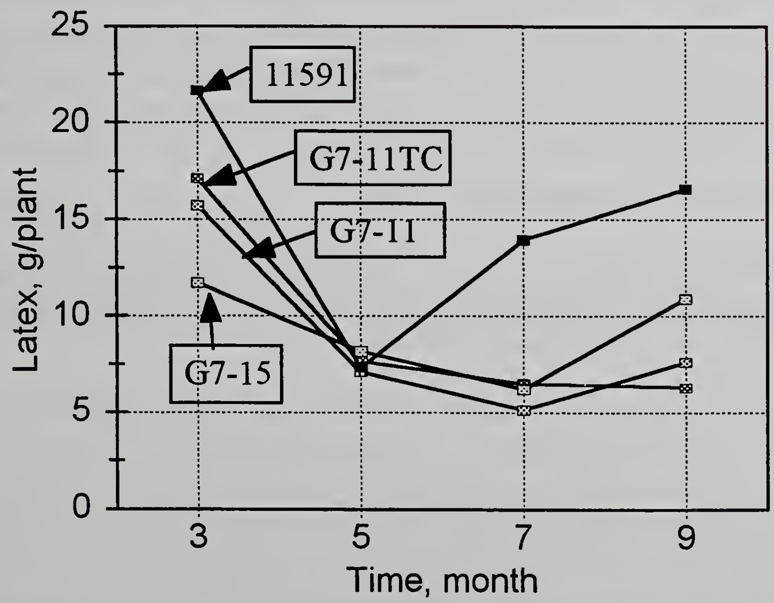

Figure 4. Relation between shrub latex content and season.

Particle boards made from guayule whole plant and bagasse have been undergoing physical and biological testing. Preliminary economic analysis indicates that the particle board would be competitive with other similar wood products, assuming that the bagasse can be obtained for free and fabrications are made 50 km from the source site. We were able to impregnate wood with resin extracts, and these samples are also undergoing various types of pest control tests.

INTERPRETATION: Comparable latex analyses at different locations could be obtained by adhering closely to the procedures developed, particularly in the use of different types of blenders. For the actual latex extraction process, shrubs must be processed soon after harvest or treated with water to maintain latex extractability if there are chances for delays occurring between harvest and processing. For commercial purposes, an adequate coordination between shrub harvest and the latex extraction process must be made to insure that the shrubs do not get dehydrated. Shrubs should be ground in the extraction solution without going through the dry chipping and flaking steps previously used in the solid rubber extraction method.

Fabricating particle boards would be a way to dispose of waste bagasse and at the same time increase the economics of guayule culture.

FUTURE PLANS: We plan to continue the latex studies with the support of a Fund for Rural America grant, which includes determining the effect of season and variety on the latex content of shrubs, storage and chemical pretreatment of shrubs, and latex characterization. Experimental work includes shrub storage in the open atmosphere and in water, and the use of other antioxidants or completely eliminating them to decrease the cost of shrub preparation. Related investigations will be done on whole shrub latex extraction to test the hypothesis that grinding the shrub directly in the extracting solution without atmospheric contact would maximize latex extraction and stability.

We will continue to provide guayule materials to cooperators for various types of pest control tests. In this endeavor, different species and lines of guayule will be included because it is known that the composition of guayule lines is different. Where possible, attempts will be made to identify the chemicals responsible for the insect control properties through cooperative work with other agencies. Existing cooperative projects will continue with the possibility of establishing a Cooperative Research and Development Agreement (CRADA) to develop uses for the waste bagasse to make blends and other types of high-valued, commercially useful wood products.

COOPERATORS: K. Cornish, USDA-ARS-PWA, Albany, CA; J.A. Youngquist, USDA-Forest Products Laboratory, Madison, WI; Poo Chow, Natural Resources and Environmental Sciences, University of Illinois, Urbana, IL; D.T. Ray and D.K. Stumpf, Plant Sciences, The University of Arizona, Tucson, AZ.

GUAYULE BREEDING AND GERMPLASM EVALUATION

T.A. Coffelt and D.A. Dierig, Research Geneticists and F.S. Nakayama, Research Chemist;
G. Leake, S. Vinyard, K. Eggemeyer, G. Dahlquist, A. Kaiser,
and P. Tomasi, Research Technicians

PROBLEM: Latex allergies caused by Heavea latex are becoming a serious health problem, and so alternative sources of hypoallergenic latex are needed. One possible source is guayule, but higher yielding, faster growing, and easier to establish germplasm is needed for it to be successful as a viable new crop. The objectives of these studies were: 1) to evaluate the survival rate and plant height and width of advanced germplasm lines one and two years after transplanting; and 2) to determine the latex content of the lines after three years growth.

APPROACH: Field tests for evaluating plant survival rate, height and width, and latex content were conducted at the Maricopa Agricultural Center (MAC) on 20 advanced lines compared to two checks (11591 and N-565). Lines were transplanted in April 1995. Lines were planted in a randomized complete block design with four replications.

Objective 1: Survival ratings and plant height measurements were taken in February 1996; plant survival, and height and width measurements were taken in March 1997. Measurements were made on all surviving plants and averaged for each plot.

Objective 2: Plant latex content was determined in spring 1998. Two representative plants from each plot were harvested, chipped, and analyzed for latex content by methods developed at the USWCL.

FINDINGS:
Objective 1: G7-14, N9-4, and N7-2 were rated the best overall lines for plant growth the first year, while N8-5, N7-5, G1-10, N6-2, P10-4, and P10-5 were rated the worst (Table 1). There were significant differences among lines in plant growth rate for the two years. For example, G7-14 grew the most the first year, while 11591, N-565, and most of the other lines grew more the second year. All lines except N-565 had a plant height to width ratio greater than one.

Objective 2: P10-4 had significantly more latex than the best check (N-565), and 14 other lines had more latex than N-565. N9-4 had some of the largest plants in addition to high latex content. However, it had poor plant survival ratings. G7-14 had the best plant survival and was among the largest in plant size, but had low latex compared to the other lines.

INTERPRETATION: Variability within and among guayule germplasm lines was significant for all traits studied in all experiments, thus indicating room for improvement in these traits through selection and other breeding techniques. Lines such as N9-4 and G7-14 in particular show that there is room for improvement over the checks. Selection within N9-4 for improved plant survival and within G7-14 for higher latex content should offer even greater advancements in improving latex yields of guayule. The lines evaluated in this study should serve as excellent sources of germplasm

Table 1. Plant stands, heights, widths, and latex contents of 22 guayule germplasm lines grown at MAC from 1995 to 1998.

LINE	1996 STAND (%)	1996 HEIGHT (cm)	1997 STAND (%)	1997 HEIGHT (cm)	1997 WIDTH (cm)	1998 LATEX (%)
G7-14	99.3	40.6	98.5	52.1	45.9	2.26
P10-4	97.0	27.6	91.0	34.6	28.9	4.22
11591	97.0	33.7	96.3	54.7	46.1	2.36
P3-11	95.5	30.6	92.5	43.0	38.1	4.07
N9-3	94.0	29.3	90.0	46.5	41.5	3.57
N6-3	91.5	27.0	86.3	38.9	34.8	3.54
G1-10	91.3	24.0	89.8	37.1	31.4	3.24
N8-10	90.8	27.0	88.5	42.2	38.7	3.41
N12-18	87.8	27.4	80.5	40.3	35.6	3.46
P10-5	86.0	24.2	82.3	36.8	30.9	2.84
G1-16	86.0	29.1	79.0	43.1	39.8	2.19
N6-2	84.5	24.3	77.5	35.3	31.3	3.49
P11-1	84.5	24.7	78.3	38.1	33.8	3.68
N13-1	83.0	30.0	82.3	46.8	42.1	3.30
O16-1	82.3	29.2	80.5	48.1	43.2	3.26
N-565	80.0	25.1	79.3	41.8	43.7	3.09
N7-5	79.8	24.0	72.8	34.0	31.6	3.55
N8-5	75.3	23.8	74.5	35.1	32.2	4.01
N7-2	75.0	31.2	72.5	48.9	44.5	2.73
N8-1	61.0	26.2	58.0	42.7	39.0	3.47
N9-4	61.0	31.9	61.8	51.1	47.3	3.91
P10-3	56.5	25.0	56.5	40.5	37.1	3.01
LSD	15.6	5.2	16.7	6.5	6.2	1.01

for cultivar development in guayule.

FUTURE PLANS: We will continue to evaluate germplasm lines for superior traits such as reduced variability among plants. Improved lines already selected for these traits were transplanted at MAC in 1998 for evaluation in 1999. Selection will continue both within and among lines for improved characteristics. Superior lines identified from these experiments will be considered for possible release as improved germplasm. Additional studies will also be conducted to try better to identify how much variability within lines is due to genetic vs. environmental factors. These studies will all involve close cooperative work with scientists at the various locations involved in guayule research.

COOPERATORS: D.T. Ray and D. Stumpf, Plant Sci.. Dep., Univ. of Arizona, Tucson, AZ; M.A. Foster, Texas Agric.. Exp. Station, Texas A&M Univ., Pecos, TX; R.A. Backhaus, Dep. Botany, Arizona State Univ., Tempe, AZ; W. Coates, Office of Arid Land Studies, Univ. of Arizona, Tucson, AZ; A. Estilai, Dep. Botany and Plant Sciences, Univ. of California, Riverside, CA; K. Cornish, USDA-ARS-PWA-WRRC, Albany, CA; W.W. Schloman, Jr., Dep. Chemistry, Univ. of Akron, Akron, OH; F.J. Adamsen and D.J. Hunsaker, USWCL, Phoenix, AZ.

ENVIRONMENTAL AND PLANT AGE EFFECTS ON GUAYULE GROWTH AND LATEX CONTENT

T.A. Coffelt and D.A. Dierig, Research Geneticists and F.S. Nakayama, Research Chemist
G. Leake, S. Vinyard, K. Eggemeyer, G. Dahlquist, A. Kaiser,
and P. Tomasi, Research Technicians

PROBLEM: Environment and plant age at harvest are known to affect the size and latex content of guayule plants. This information is lacking on newly released germplasm lines that have been selected for faster growth and/or higher latex content. The information is needed on these lines in order to develop improved planting and harvesting schemes which take advantage of the superior qualities of these lines.

APPROACH: Three newly released germplasm lines (AZ 1, AZ 2, and AZ 3) and an advanced breeding line (G7-14) were transplanted at the University of Arizona Maricopa (MAC) and Marana Agricultural Research Farms in the spring of 1995 and 1996. One- and two-year-old plants were evaluated for height, width, and latex content in the spring of 1997 (Table 1). Two- and three- year-old plants were evaluated for latex content in the spring of 1998 (Table 2). Two representative plants per plot were harvested for latex analysis. The two plants were chipped together, a subsample of the chipped material was taken, and latex determined by a method developed at the USWCL. Lines were planted in a completely randomized design with four replications at both locations both years.

Table 1. Main effects (plant age, location, and line) for plant height, width, and latex concentration of four lines grown at two locations in 1997.

MAIN EFFECT	HEIGHT (cm)	WIDTH (cm)	LATEX (%)
AGE			
ONE YEAR	42.8 b	42.2 b	0.93 b
TWO YEARS	57.4 a	57.2 a	1.46 a
LOCATION			
MAC	39.4 b	33.9 b	0.60 b
MARANA	60.8 a	65.5 a	1.79 a
LINE			
AZ 1	41.6 c	42.0 c	1.65 a
AZ 2	50.5 b	52.4 ab	1.13 b
G7-14	55.5 a	55.3 a	0.94 b
AZ 3	52.7 ab	49.1 b	1.07 b

FINDINGS: Two-year-old plants were significantly taller and wider and had more latex than one-year-old plants (Table 1), while three-year-old plants had a significantly higher latex concentration than two-year-old plants (Table 2). Plants grown at Marana were significantly taller and wider in 1997, and higher in latex both years, than those grown at MAC. Although AZ 1 had a higher latex concentration than the other lines in 1997, in 1998 it was higher in latex than only G7-14. While there was an age x location effect for latex content in 1997, this interaction was not significant for the two- and three-year-old plants in 1998. The other interaction effects were not significant for latex concentration in either year. Interaction effects for height and width were generally not significant sources of variation, especially compared to the main effects.

Table 2. Main effects (plant age, location, and line) for latex content of four linesgrown at two locations in 1998.

MAIN EFFECT	LATEX (%)
AGE	
TWO YEARS	1.06 b
THREE YEARS	1.57 a
LOCATION	
MAC	0.85 b
MARANA	1.79 a
LINE	
AZ 1	1.59 a
AZ 2	1.27 ab
G7-14	1.13 b
AZ 3	1.28 ab

INTERPRETATION: Although older plants were generally higher in latex and larger than younger plants, the opportunity exists for selecting lines that could be harvested in 12 to 18 months under favorable environmental conditions. More experiments need to be conducted to identify the environmental factor(s) that are responsible for the significant differences in plant growth between MAC and Marana in this study.

FUTURE PLANS: We will evaluate known environmental differences between MAC and Marana such as irrigation frequency and amount, water quality, fertility, soil type, pest (weed, insect, and disease) problems, crop rotation, and temperature to determine the factor(s) responsible for the increased plant size and latex content at Marana vs. MAC. Initial data indicate soil fertility may be a primary factor. We will work to develop harvesting schedules, planting methods, crop rotations, and other approaches for maximizing latex yield. These studies will involve close cooperative work with scientists at the various locations involved in guayule research as well as other management units at the USWCL.

COOPERATORS: D. Ray and D. Stumpf, Plant Sci.. Dep., Univ. of Arizona, Tucson, AZ; M. Foster, Texas A&M Univ., Pecos, TX; F. Adamsen and D. Hunsaker, US Water Conservation Lab, Phoenix, AZ; R. Backhaus, Dep. Botany, Arizona State Univ., Tempe, AZ; A. Estilai, Dep. Botany and Plant Sci., Univ. of California, Riverside, CA; K. Cornish, USDA-ARS-WRRC, Albany, CA; W. Schloman, Jr., Dep. Chemistry, Univ. of Akron, Akron, OH; W. Coates, Office of Arid Land Studies, Univ. of Arizona, Tucson, AZ.

ENVIRONMENTAL AND PLANT AGE EFFECTS ON GUAYULE REGROWTH

T.A. Coffelt and D.A. Dierig, Research Geneticists and F.S. Nakayama, Research Chemist
G. Leake, S. Vinyard, K. Eggemeyer, G. Dahlquist, A. Kaiser,
and P. Tomasi, Research Technicians

PROBLEM: Multiple or successive harvests from a single planting of guayule shrub would greatly reduce production costs, because replanting would not be required. Data is lacking on the regrowth potential of the newer germplasm lines as well as the effects of environment, plant age, and genotype on the amount of regrowth after initial harvest for these lines.

APPROACH: Three newly released germplasm lines (AZ 1, AZ 2, and AZ 3) and an advanced breeding line (G7-14) were transplanted at the University of Arizona Maricopa (MAC) and Marana Agricultural Research Farms in the spring of 1995 and 1996. Initial harvests were made in the Spring of 1997 from one- and two-year-old plants and in the spring of 1998 from two- and three-year-old plants. Two harvested plants per plot have been monitored periodically for their ability to regrow (% survival). Plant height and width were also measured. Lines were planted in a completely randomized design with four replications at both locations in both years.

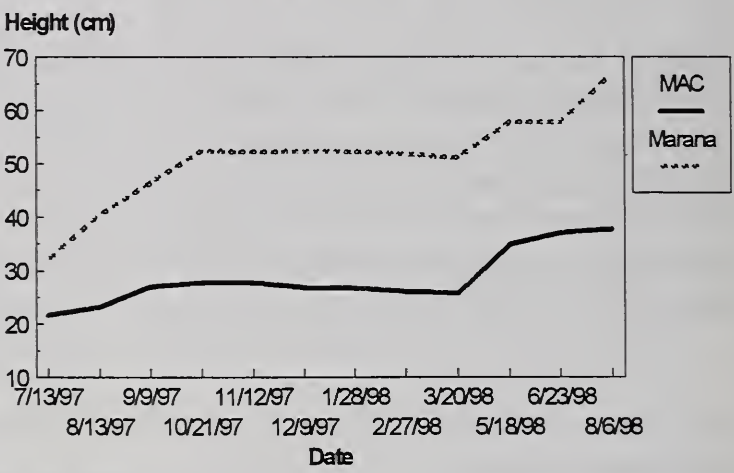

Figure 1. Regrowth plant height at two locations.

FINDINGS: While the number of plants with regrowth did not differ significantly between locations, the height and width of plant regrowth was significantly greater at Marana than at MAC at each measurement date (Figs. 1 and 2). Plant age at harvest (one- vs. two-years-old) did not affect the number of plants with regrowth or the size of those plants after regrowth (Figs. 3 and 4). AZ 2, AZ 3, and G7-14 all had excellent regrowth capabilities (>85%) compared to AZ 1 (<50%). AZ 1 also had significantly smaller plant height and width than the other lines at each measurement date (Figs. 5 and 6). However, this line has more latex in the initial growth than the other lines. Results also showed that plants reached a peak size for the season by December and then actually reduced in width before starting to regrow again in March (Figs. 1-6).

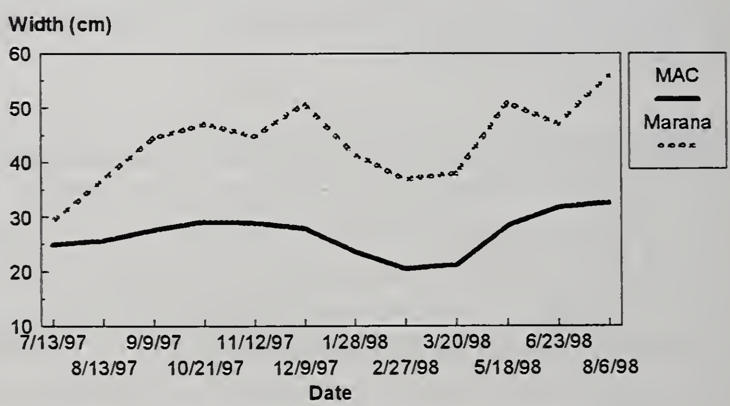

Figure 2. Regrowth plant width at two locations.

INTERPRETATION: The cause of the large environmental difference observed in this study and in the initial growth study could be due to one or a combination of several factors such as irrigation water quality and/or quantity, soil type, fertility, temperature, etc. Research is underway to try to better define the cause of these results. These plants were all harvested in the spring with good growing conditions until the fall. Previous research with other lines has shown that harvesting later in the year has increasing adverse effects on plant regrowth than in the spring. Preliminary observations from another study with these lines indicates similar trends. The strong genotypic effect on the ability of plants to regrow was also observed in other lines in the MAC test (results not shown). If a grower is planning to use a multiple harvesting system, the regrowth capabilities of a guayule line selected becomes a significant factor. However, results from this study indicate that, with the right genotype and favorable environmental conditions following an initial harvest, a multiple harvesting system should be viable for guayule. The number of successive harvests and the frequency of these harvests still need to be determined. Quantity and quality of the latex produced from the regrowth material also still needs to be determined.

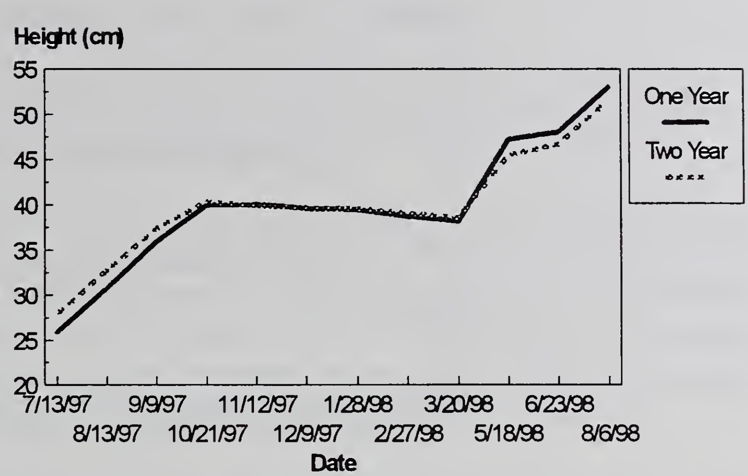

Figure 3. Regrowth plant height from plants harvested at two plant ages.

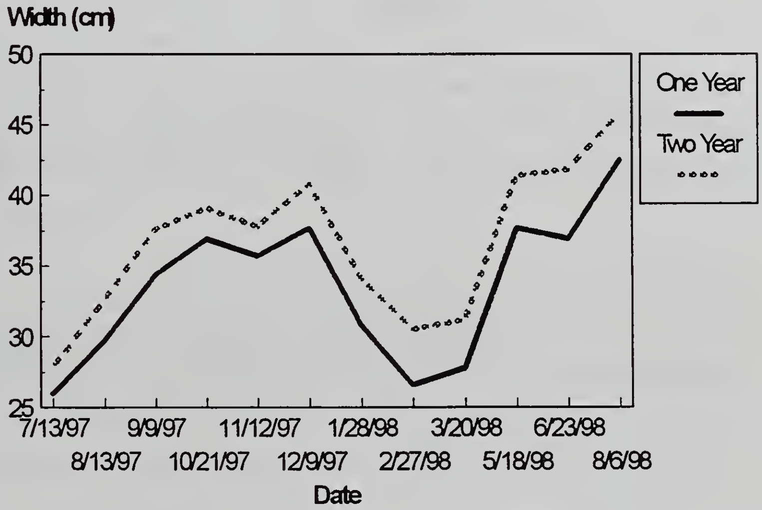

Figure 4. Regrowth plant width from plants harvested at two plant ages.

FUTURE PLANS: We will cooperate in studies to develop harvesting schedules and methods for maximizing latex yield. Regrowth from these plants will be monitored until the spring of 1999, when plants with regrowth will be harvested for latex analyses. Comparisons will be made between two years of regrowth from one- and two-year-old plants and between one year of regrowth from two- and three-year-old plants. The effects of environment and genotype on latex will also be determined. These studies will all involve close cooperative work with scientists at the various locations involved in guayule research, as well as other scientists at the USWCL.

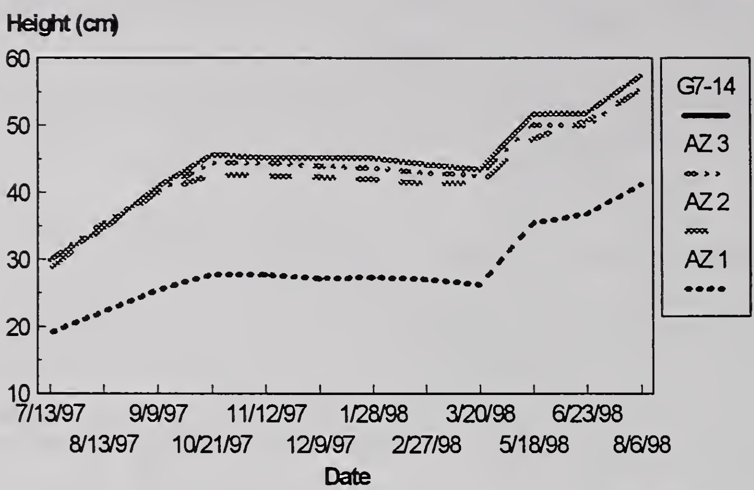

Figure 5. Regrowth height of plants of four lines.

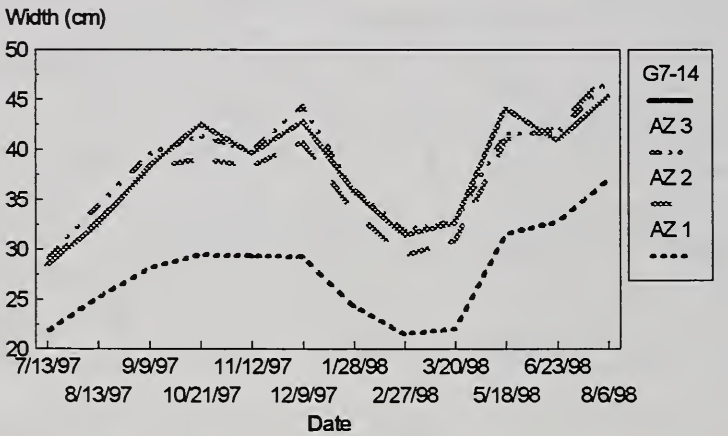

Figure 6. Regrowth width of plants of four lines.

COOPERATORS: D. Ray and D. Stumpf, Plant Sci.. Dep., Univ. of Arizona, Tucson, AZ; M. Foster, Texas A&M Univ., Pecos, TX; F. Adamsen and D. Hunsaker, US Water Conservation Lab, Phoenix, AZ; R. Backhaus, Dep. Botany, Arizona State Univ., Tempe, AZ; A. Estilai, Dep. Botany and Plant Sci., Univ. of California, Riverside, CA; K. Cornish, USDA-ARS-WRRC, Albany, CA; W. Schloman, Jr., Dep. Chemistry, Univ. of Akron, Akron, OH; W. Coates, Office of Arid Land Studies, Univ. of Arizona, Tucson, AZ.

LESQUERELLA GERMPLASM IMPROVEMENT

D.A. Dierig, T.A. Coffelt, Research Geneticists; Francis Nakayama, Research Chemist; Aaron Kaiser, Gail Dahlquist, Greg Leake, and Pernell Tomasi, Research Technicians

PROBLEM: Lesquerella seed could provide U.S. industrial markets with a source of hydroxy fatty acids. In the past, these markets have been satisfied by imports of castor for many types of industrial applications, such as paints, coatings, lubricants and greases. Imports of castor oil and derivatives amount to more than 65,000 tons per year at a value exceeding $100 million per year. The unique chemical structure of the oil from Lesquerella, although similar to castor, offers distinct advantages for development of other applications, as well as being a partial replacement for castor oil.

Some of the germplasm of *Lesquerella* species previously collected in the wild by this laboratory has only limited amounts of seed, and some have not yet been evaluated. Seed increases and passport information are necessary to successfully utilize these accessions in our breeding program. It is also necessary to make seed available to other researchers through the National Plant Germplasm System (NPGS).

Improvements in seed oil characteristics are necessary for commercialization of this potential crop. Industry representatives indicate that seed oil content should be near 35 % to be economically profitable. Therefore, a major goal of this breeding program is to develop lesquerella germplasm with a higher oil content than the 35 % minimum.

APPROACH: Seeds originating from past collection trips between 1993 and 1996 from the United States were field grown at the U. S. Water Conservation Laboratory (USWCL) for seed increase and evaluation. When only limited seed quantities were available, seeds were started in the greenhouse in October and transplanted into the field in December through January. When plants began to flower, screen cages were placed over individual plots and supplied with a nucleus of honey bees for pollination in order to prevent cross pollination with other accessions. Plant growth measurements were taken throughout the season. After harvest, seeds from each accession were analyzed for oil content and composition. Following harvest, seeds of increased accessions were sent to the Agriculture Research Service (ARS) Curator in Pullman, Washington, to be entered in the NPGS.

Three recurrent populations for increased oil and hydroxy fatty acid yields were repeated for the 1997-1998 season. The populations were planted at The University of Arizona, Maricopa Agricultural Center. Five hundred plants from each population were harvested, analyzed and compared to an unselected check population.

FINDINGS: Forty-nine accessions from 23 species were increased this year at the USWCL (Table 1). Some accessions could not be successfully grown outdoors in this climate and, as a result, had to be grown in the greenhouse. Seed yields were reduced since plants had to be hand pollinated to obtain seed because of self-incompatibility. Descriptive data on plant growth were also collected. Collection number 1920, *L. fendleri* was a completely different biotype. It acted as a perennial

instead of an annual and had a low prostrate growth. There were adequate amounts of seed harvested from many of these accessions so they could be sent for entry into NPGS. This and the previous year evaluation produced increased seed of 61 accessions from 22 species which were sent to ARS, Pullman, Washington. Ten of these species previously were unrepresented in the NPGS. The germplasm will now be available for access to researchers all over the world.

Table 1. Results of evaluation of Lesquerella species increased and evaluated at the USWCL, 1997-98.

	Collection	Species	Oil (%)	20:1-OH (%)	Seed weight (g)	1st Flower (date)
1	A1819	*fendleri*	20.81	48.93	104.43	Mar. 3
2	A1830	*gordonii*	23.79	55.06	4.62	Mar. 9
3	A1833	*gordonii*	21.04	58.24	11.13	Jan. 12
4	A1851	*fendleri*	20.92	47.64	53.63	Mar. 31
5	A1853	*fendleri*	NA*	NA	0.85	Feb. 3
6	A1859	*pinetorum*	13.35	49.20	2.23	Jan. 18
7	A1860	*cinerea*	NA	NA	0.03	NA
8	A1861	*cinerea*	NA	NA	0.14	NA
9	A1869	*cinerea*	23.85	51.08	62.26	Feb. 24
10	A1876	*rectipes*	15.42	49.20	6.53	Jan. 5
11	A1879	*intermedia*	21.32	42.94	21.93	Mar. 9
12	A1882	*intermedia*	23.59	48.41	12.91	Mar. 2
13	A1893	*arizonica*	NA	NA	0.02	NA
14	A1894	*arizonica*	NA	NA	0.20	NA
15	A1909	*fendleri*	21.32	49.75	12.49	NA
16	A1911	*ovalifolia*	19.77	50.30	42.82	NA
17	A1920	*fendleri*	15.78	43.52	1.20	NA
18	A1924	*fendleri*	22.97	47.33	5.22	NA
19	A1930	*intermedia*	18.93	44.80	2.72	Mar. 18
20	A1931	*cinerea*	NA	NA	0.19	Mar 2
21	A1932	*fendleri*	21.16	50.67	143.88	NA
22	A2202	*densiflora*	16.01	60.00	3.08	Jan. 26
23	A2204	*recurvata*	16.58	69.03	1.02	Jan. 22
24	A2217	*lasiocarpa*	25.58	53.82	18.56	Jan. 12
25	A2219	*argyraea*	19.74	56.44	17.21	Jan. 22
26	A2226	*fendleri*	20.38	50.47	40.62	Mar. 2
27	A2228	*lasiocarpa*	24.39	52.92	64.86	Jan. 19

28	A2232	*lindheimeri*	25.41	83.70	12.98	Jan. 26
29	A2239	*argyraea*	NA	NA	0.05	Mar. 9
30	A2243	*grandiflora*	32.54	58.16	19.34	Dec. 16
31	A2245	*argyraea*	22.07	57.56	6.54	Jan. 29
32	A2246	*grandiflora*	26.76	53.08	8.36	Mar. 2
33	A2247	*grandiflora*	24.99	52.07	13.58	Mar. 2
34	A2249	*recurvata*	14.62	64.67	3.73	Jan. 26
35	A2250	*recurvata*	14.58	61.55	5.13	Feb. 2
36	A2258	*fendleri*	20.82	48.01	4.81	Mar. 20
37	A2279	*mcvaughiana*	15.23	51.14	6.50	Feb. 17
38	A2306	*fendleri*	18.38	NA	25.21	NA
39	A2403	*douglasii*	NA	NA	0.58	Mar. 2
40	A2921	*gracilis*	18.52	65.76	2.72	Jan. 22
41	A2925	*angustifolia*	12.47	61.94	2.10	Mar. 20
42	A2927	*angustifolia*	13.29	57.32	14.69	Mar. 2
43	A2928	*gracilis*	22.32	48.23	10.48	Jan. 30
44	A2996	*rectipes*	27.36	56.17	10.49	Feb. 6
45	A3042	*luduvicana*	21.88	48.31	2.98	Feb. 5
46	A3178	*montana*	NA	NA	0.50	Jan. 27
47	A3179	*hemiphysaria*	NA	NA	0.05	Jan. 28
48	A3186	*multiceps*	23.91	51.33	2.97	Jan. 27
49	A3219	*pallida*	23.99	81.72	5.74	Mar. 9

*data not available

The recurrent population for high oil content ranged between 17 and 34%. The population mean was 28.2% and standard error of 2.2%, compared to an unselected population of 25%, 2.5% standard error. The control population ranged between 18 and 31%. The average of the selected lesquerolic acid population was only 1% above the control population. This could be due to lack of seed maturity at the time of analysis since many samples had very low values for C20:1-OH (lesquerolic acid) and higher than normal values for C18:1.

INTERPRETATION: Considering the cost of obtaining seed from germplasm collection trips, the seed from this project is very valuable. Special care must be taken to assure that seed is increased without contamination from other accessions, evaluated to obtain usable information about the accession, and properly handled from harvest to storage. The seed deposited into NPGS benefits researchers nationally and internationally. It also has a long term benefit to our breeding program. The results for the recurrent selection for high oil shows a significant increase compared to the control population. This indicates that progress has been made in developing a population with

higher oil content and brings this potential crop closer to commercialization.

FUTURE PLANS: The germplasm evaluation will be continued for this next season. We plan to collect more germplasm in Mexico in 1999. Plans are contingent on obtaining a funding grant through ARS, National Plant Germplasm Office and on Permits for collection through the Mexican Government. If more germplasm is collected, then it will be especially important to continue this project. These collection trips usually only provide very limited quantities of seed. The recurrent population is not being continued for the 1998-99 season. This has been a very labor intensive project with limited funding over the past few years. The top lines that resulted are being tested in a yield trial at Tucson and Maricopa. Following testing, lines will be made available through a public germplasm release.

COOPERATORS: R.H. Lawson, ARS-NPS; A.S. Stoner, National Germplasm Resources Laboratory, Beltsville, MD; R.Roth, J.M. Nelson, Maricopa Agricultural Center (MAC), University of Arizona, Maricopa, AZ; D.T. Ray, University of Arizona, Tucson, AZ; Vicki Bradley, Plant Germplasm Introduction Station, Pullman, WA; B. Phillips, T. Abbott, ARS, NCAUR, Peoria, IL

GENETIC AND ENVIRONMENTAL EFFECTS ON LESQUERELLA

David A. Dierig, Terry A. Coffelt, Research Geneticists; Francis S. Nakayama, Research Chemist; Pernell Tomasi, Gail Dahlquist, Aaron Kaiser, and Greg Leake, Research Technicians

PROBLEMS: *Lesquerella fendleri* (Gray) Wats., Brassicaceae, is a potential oilseed crop native to the Southwestern United States. The seed oil contains hydroxy fatty acids, similar to castor. Unique properties of the oil, along with co-products, allow additional applications that would not be in competition with castor.

Seed yields of lesquerella could be increased with hybrid seed production. A common method used to produce hybrid seed is planting completely sterile lines (no pollen) in a row next to a pollen producing line. The seed is harvested only from the sterile plants. The inheritance of the male sterile trait must first be understood in order to produce these lines, make progress faster and development of hybrid seed easier.

The effects of saline irrigation on plant development and seed production in lesquerella are unknown. Knowing the effects of different salt concentrations, plants can be selected on the basis of survival and seed production in the higher salt treatments to produce a salt tolerant population. The rate of development of fatty acids in the seed oil following anthesis is unknown. Selection of plants for elevated lesquerolic acid before the termination of flowering would allow time to cross individuals during the same season, thus reducing the time for development of improved germplasm.

APPROACH: A male sterile segregating population was planted in greenhouses at USWCL. Seeds resulted from crosses between male sterile (no pollen) and male fertile (pollen) plants. Fifty-six different lines with 9844 plants were scored at flowering for the male sterile trait. Some were reciprocal crosses, to determine if the trait is passed along only through the maternal parent. Ratios of sterile and fertile plants indicate the number of genes responsible and the dominance relationship. This was the third and final season of the study.

The response of lesquerella to salt tolerance was studied with transplants of non selected plants in 24 outdoor sand tanks at U.S. Salinity Laboratory, Riverside, CA. The targeted electrical conductivity (EC) values of the irrigation solutions were 3 (control), 6, 9, 12, 15, 18, 21, and 24 dS/m^{-1}. Each tank contained 72 plants. Three replications were planted in a randomized complete block design. The final plant survival was counted on March 31, 1998. Plant biomass and seed yields were measured at harvest. Seed was obtained from selected surviving plants from the 21 and 24 dS/m^{-1} treatments that were removed at the beginning of anthesis and transferred into an isolation cage to prevent crossing with less salt tolerant plants.

Environmental effects on the fatty acid profile development were examined in maturing seeds. Flowers of 600 individual flowers were tagged while growing in the field at two locations. Age of the seeds was determined from first day of flowering (DAF) to harvest of the pod. Seeds were

harvested at 2-day intervals from 17 to 37 DAF. Seed samples were stored at -80 C following harvest. After seed collections were completed, samples were arranged in three replications of a completely randomized design and analyzed on a gas chromatograph. Seed weight and fatty acids were evaluated.

FINDINGS: Ratios of reciprocal crosses from the two previous years of this study (data not shown) indicate that a cytoplasmic gene, when present, can restore fertility of expected male steriles. Data from Table 1, combined with the two previous years data, indicate that two nuclear genes with epistatic effects control male sterility. Although ratios of 3:1 and 1:1 typically indicate that a single gene controls the trait, other ratios such as the 9:7, 6:10*, and 4:12* (*both parent gene pairs are not heterozygous) are characteristic of an epistatic effect between two nonlinked genes. The proposed genotype for fertile phenotypes would be A_B_, where the _indicates the second allele could be either dominant or recessive. The proposed sterile genotype is A_bb, aaB_ or aabb.

Table 1. Male fertility: sterility segregation ratios and chi square tests for expected ratios more than three generations of crosses between male fertile and male sterile phenotypes, and male fertile by male fertile phenotypes.

Expected Ratio	Number of Families FXF[1]	SXF[1]	Total	Observed Fertile	Sterile	Partial	Total	χ^2	P
3:1	5	7	12	1493	461	49	2003	0.17	0.68
1:1	0	13	13	909	858	56	1823	0.01	0.92
9:7	0	5	5	567	416	26	1009	0.0	0.99
14:2	0	3	3	480	56	12	548	0.0	0.99
4:12	0	4	4	207	539	42	788	0.01	0.92
6:10	0	3	3	232	371	18	621	0.0	0.99
all sterile	0	5	5	128	842	57	1027	13.25	0.0
all fertile	5	3	8	1274	41	10	1325	0.0	0.99

[1]S = Sterile phenotypes, F = Fertile phenotypes

Table 2. Results of the effects of salinity treatment on lesquerella planted in outdoor sand tanks at Riverside, CA.

Treatment (dS/ m^{-1})	Survival (%)	Biomass (g)	Seed Yield (g plant)
3 (control)	36	57.6	1.9
6	67	43.4	2.0
9	71	37.4	2.0
12	83	38.9	3.1
15	83	31.1	3.1
18	25	13.8	1.8
21	21	1.6	0.2
24	4	*NA	*NA

*data not available

Salinity reduced transplant survival in treatments that exceeded 15 dS/ m^{-1} (Table 2). This could be attributed to the stunted and confined roots of these transplants that never spread beyond the initial

root ball. Survival in the 24 dS/ m^{-1} was poor and the treatment was discontinued after April. The remaining plants from these two treatments were moved into an isolation cage for seed harvest. Plant biomass was reduced as salinity treatments increased (Table 2). Seed yield per plant was reduced when treatments were above 15 dS/ m^{-1}. The highest seed yields per plant were obtained at the 12 and 15 dS/ m^{-1} treatments. There were no differences between the control (3 dS/ m^{-1}) and the 6 and 9 dS/ m^{-1} treatments. Lesquerolic acid content was stabilized by 33 days after flowering (DAF) (Table 3). These data correspond to the data collected in last years' study at the same location. Although seed moisture appeared to be high at the end of the study, 60 %, the seed dry weights appear to be stable by 31 DAF.

Table 3. Seed weights, seed moisture contents, and fatty acid profile of seed oil at two day intervals from 17 to 37 days after flowering.

Days after Flower	Date	Fresh Weight 1000 Seeds	Dry Weight 1000 Seeds	Moisture (%)	C18:2 (%)	C18:3 (%)	C20:1-OH (%)
17	April 25	0.368	0.099	0.73	37.2	23.9	0
19	April 27	0.518	0.116	0.78	40.7	26.9	0
21	April 29	0.958	0.213	0.78	32.0	24.2	trace
23	May 1	1.175	0.339	0.71	34.1	24.4	trace
25	May 3	1.155	0.335	0.71	21.1	19.5	20.0
27	May 5	1.453	0.450	0.69	14.9	17.0	32.6
29	May 7	1.509	0.488	0.68	11.9	17.5	36.9
31	May 9	1.628	0.599	0.64	11.1	16.9	42.9
33	May 11	1.351	0.561	0.61	8.6	16.1	47.8
35	May 13	1.551	0.616	0.60	8.0	15.7	50.3
37	May 15	1.360	0.545	0.58	7.4	16.6	48.4

INTERPRETATION: The inheritance of male sterility in lesquerella is likely controlled by two nuclear genes located on different chromosomes (epistatic effects). There are also non-nuclear (cytoplasmic) gene effects that, when present, restore fertility of sterile genotypes. The cytoplasmic effects are of interest for hybrid seed production. This is the first set of genetic markers reported for lesquerella. Linkage to other traits and molecular markers will be useful in establishing a genetic map. The salinity study resulted in establishing a selected population for salt tolerance. Results show that there is variability for salt tolerance within the population.

Based on data from the fatty acid profile study, seed could be harvested for lesquerolic acid 33 DAF. Since these were destructive measurements, it cannot be definitely assumed that lesquerolic acid content would not further increase if seed were left unharvested. However, last years' data indicated that there was no statistical difference in values from 27 to 70 DAF. The conclusion from this is

selections could be sampled after 35 DAF to allow for controlled crossing between selected plants. This would reduce the time needed to develop improved germplasm.

FUTURE PLANS: This was the final year for the male sterility study. The results of the three seasons are being submitted for publication. We continue to collaborate with the ARS, U.S. Salinity Laboratory, Riverside, CA on a salinity study. A second year study is now in progress. This year's study was planted by direct seeding instead of transplants. Also, seed selected for salt tolerance from the first year was used in the second year study, with another line selected for plant height, plus the same population used in the first year study. The study on fatty acid development in lesquerella seeds is completed. However, data were collected at 19, 25, 31, and 37 DAF to analyze the development of seed oil content in this study . The analysis is not yet complete and will determine if this aspect of the study may continue.

COOPERATORS: R.L. Roth, University of Arizona, Maricopa, AZ; Catherine M. Grieve and Michael C. Shannon, ARS, US Salinity Lab., Riverside CA; D.T. Ray, University of Arizona, Tucson, AZ;

1998 Publications

Technology Transfer / Weekly Reports

Support Staff

Cooperators

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[1] The WCL# corresponds to the item number on the USWCL Publications List. Please use the WCL# to request USWCL Publications.

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TECHNOLOGY TRANSFER

Following are summaries of the laboratory's major technology transfer accomplishments for 1998.

Irrigation and Water Quality

Scientist: Bert Clemmens - Simulation of surface irrigation
Bert Clemmens of the Irrigation and Water Quality Unit, Phoenix, AZ, and Fedja Strelkoff, a University of Arizona cooperator, led the development of a new generation of user-friendly software for the simulation of surface irrigation events. This process-based model predicts the flow of water over the soil surface to determine both the distribution of infiltrated water and runoff. The new version of the software, commissioned by the Natural Resources Conservation Service, is being used to design surface irrigation systems.

Scientist: Doug Hunsaker - Prediction of soil evaporation
Studies on crop water use conducted by Doug Hunsaker of the Irrigation and Water Quality Unit, Phoenix, AZ, have identified and clarified an important issue in determining future state water duties for farmers. The studies quantified the amount of soil evaporation occurring after irrigation events, an aspect currently neglected in determining water duties. As a result, farmers have been virtually unable to meet the target irrigation efficiency of 85%, which is difficult even without considering the loss due to soil evaporation. The study results should assist farmers and the Arizona Department of Water Resources in their negotiations on future water duties.

Scientist: Floyd Adamsen - Use of digital cameras for analysis of plant status
Floyd Adamsen of the Irrigation and Water Quality Management Unit and scientists in the Environmental and Plant Dynamics Unit, Phoenix, AZ, have developed an inexpensive method to predict optimum harvest dates for wheat and to collect other important crop data. The new approach, using a color digital camera costing less than $1000 and off-the-shelf software, compares favorably with measurement of the chlorophyll content of the leaves and established methods using hand-held radiometers, which cost an order of magnitude more than the camera system. These results should assist consultants and farmers in timing harvest dates.

Scientist: John Replogle - Assessment of flow-measurement accuracy
John Replogle, Brian Wahlin, and Bert Clemmens of the Irrigation and Water Quality Management Unit, Phoenix, AZ, analyzed the accuracy of flow measurement and monitoring stations for the Imperial Irrigation District, Imperial, CA, and for the U.S. Army Corps of Engineers, Chicago, IL. These studies documented the accuracy of instantaneous flow rates and annual volumes for such measurement stations. Since ARS is a neutral party, these analyses are being used to settle water rights disputes.

Environmental and Plant Dynamics

Scientists: Dave Dierig, Anson Thompson, and Terry Coffelt - Release of three lesquerella germplasm lines

The first public release of improved germplasm lines of lesquerella was made by Dave Dierig, Anson Thompson, and Terry Coffelt of the Environmental and Plant Dynamics Unit, Phoenix, AZ, after three generations of recurrent selection. Two of the lines yield higher lesquerolic acid and the other higher seed oil than the unselected populations. These germplasm lines should be valuable sources of germplasm for cultivar development and subsequent commercialization of lesquerella, which is potentially an attractive new crop for production in the arid southwest.

Scientists: Dave Dierig, Anson Thompson, and Terry Coffelt - Release of six guayule germplasm lines

Six guayule germplasm lines were jointly released by the Agricultural Experiment Station, University of Arizona, and the USDA-ARS. ARS scientists were Dave Dierig, Anson Thompson, and Terry Coffelt of the Environmental and Plant Dynamics Unit, Phoenix, AZ; Dennis Ray of the University of Arizona was a cooperating scientist. These lines were released for uniformity of plant appearance, fast growth, high resin content, and/or high rubber yielding ability. The faster growth of these lines could decrease time to initial harvest from three to two years, which would decrease cost of production and make guayule a more attractive new crop.

Scientist: Terry Coffelt - Release of VGP 10 peanut germplasm line

VGP 10 peanut germplasm line was jointly released by the USDA-ARS and the Virginia Agricultural Experiment Station. Terry Coffelt of the Environmental and Plant Dynamics Unit, Phoenix, AZ, cooperated with R.W. Mozingo of the Virginia Agricultural Experiment Station in developing this germplasm. VGP 10 was released for its large seed size, early maturity, and high oleic to linoleic fatty acid ratio. Larger seed size is desirable for increasing exports and certain domestic markets, while the higher oleic to linoleic fatty acid ratio indicates a longer shelf life. This germplasm will be valuable to peanut breeders seeking to develop new cultivars with longer shelf life, earlier maturity, and larger pod and seed size.

Scientist: Terry Coffelt - Release of VGP 11 peanut germplasm line

VGP 11 peanut germplasm line was jointly released by the USDA-ARS and the Virginia Agricultural Experiment Station. Terry Coffelt of the Environmental and Plant Dynamics Unit, Phoenix, AZ, cooperated with R.W. Mozingo and D.A. Herbert, Jr. of the Virginia Agricultural Experiment Station in developing this germplasm. VGP 11 was released for its partial resistance to southern corn rootworm, good blanchability, and more desirable pink seed testa color. The only currently resistant cultivar to southern corn rootworm (NC 6) has been declining in popularity due to lower yields, poor blanchability, and a tan seed testa color. VGP 11 yields higher than newer cultivars on soils with a rootworm problem, has a more desirable pink seed testa, better blanchability than NC 6, and more resistance to southern corn rootworm than cultivars other than NC 6. This germplasm should be valuable to growers seeking a higher yielding resistant cultivar to plant in heavier soils where southern

corn rootworm is a problem and to breeders developing germplasm and cultivars with increased resistance to southern corn rootworm, while maintaining high levels of blanchability, yield, and the pink seed testa color desired by industry.

Scientists: M. Susan Moran and Jiaguo Qi - Methods for reflectance factor retrieval and age processing

Susan Moran and Jiaguo Qi of the Environmental and Plant Dynamics Unit, Phoenix, AZ, developed methodologies for calibration and correction of aircraft-based spectral imagery. These methodologies will facilitate commercial acquisition of high-quality, physically-based information that could be used to monitor crop water and nitrogen stress, weed infestation and plant emergence. Field tests are being conducted at ARS facilities to quantify the accuracy and precision of the correction algorithms. The work was done under a CRADA with a commercial satellite and aircraft image provider, RESOURCE21.

WEEKLY REPORTS

Following are USWCL "ARS Weekly Activity Report" submissions for 1998. Each research scientist submits a minimum of one report per year. These reports are consolidated at ARS Area level and submitted to ARS headquarters for the information of agency and departmental management.

Neal Adam, Plant Physiologist

Research led by scientists from the USDA-ARS U.S. Water Conservation Laboratory in Phoenix has shown that plant growth (leaf photosynthesis) will be enhanced by the higher atmospheric carbon dioxide (CO_2) levels predicted for the future. Further information is needed in order to accurately model plant responses to future increases in atmospheric CO_2. This work studied the effects of increased CO_2 and nitrogen fertilizer level on plant leaf metabolism. Reductions (down-regulation) of carbon metabolism of leaves were shown to depend on the growth stage of the plant and leaf position on the plant and indicate that increases in plant growth will be limited by this down-regulation. This information will be very valuable in the efforts of modelers to accurately predict plant responses to a future higher CO_2 world. Scientists from Arizona State University and the University of Arizona cooperated in this research.

Eduardo Bautista, Agricultural Engineer

Anticipatory Control of Irrigation Delivery Systems. Researchers at the USDA-ARS U.S. Water Conservation Laboratory in Phoenix, Arizona, have been working on the development of an algorithm for scheduling canal gate operations given a known schedule of flow changes at canal turnouts. Developing methodologies for improving water flow control is difficult because of the mathematical complexity of the equations used to represent the unsteady flow of water in canals. Currently, most canal systems are operated using empirical rules and operator experience. With recent advances in computer and remote control technologies, the development of computerized control systems for canals is now more likely than ever. These control systems are expected not only to facilitate the operation of canals under their present operational rules, but are also expected to promote more flexible rules and a service that is more responsive to user needs. Providing water users with timely and accurate deliveries is critical to improving agricultural water management. Computer simulation results have shown that the resulting schedules provide improved control over scheduling approaches used in manually operated canals. Efforts are underway to test the algorithm with a large water delivery system. Irrigation districts and engineering consultants should find this technology valuable.

Herman Bouwer, Research Hydrological Engineer

Simplified procedures have been developed at the U.S. Water Conservation Lab., Phoenix, Arizona and successfully tested in the field that will increase conjunctive use of surface water, groundwater, and water reuse as essential elements in increasingly needed integrated water management. This will require more artificial recharge of groundwater for normal and long-term storage (water banking) of surface water and for soil-aquifer treatment of sewage effluent. The permeable soils (sands, etc.) preferred for surface infiltration are not always available where recharge is needed, so that less permeable agricultural or desert type soils must be used. Procedures have been developed and successfully tested in the field to predict infiltration capacities for these soils with single ring

infiltrometers to determine land requirements, relative evaporation losses, and other feasibility aspects. Equations have been developed to predict where groundwater pumping is needed and to what depth groundwater levels must be pumped down to prevent undue rises (water logging, etc.) of the groundwater levels below the infiltration systems. Experimental field plots will be installed in conjunction with two new recharge projects (one for sewage effluent and one for river water) to see how the less permeable "challenging" soils should be managed to maintain maximum infiltration rates. Unlike sands, these soils can pose problems of particle segregation due to erosion and deposition, fine-particle movement (wash-out wash-in), crusting, compaction, and pore-plugging biofilm development on the soil particles themselves.

Bert Clemmens, Research Leader
Competition for water from the Colorado River is intensifying. The Lower Colorado River Region of the U.S. Bureau of Reclamation is responsible for managing and allocating water to various users in California, Arizona, and Nevada. Forced reductions in water delivered to irrigated agriculture in Southern California is likely to occur within the next year or two. All users are required by law to develop water conservation plans. An ARS scientist from the U.S. Water Conservation Laboratory in Phoenix cooperated with Imperial Irrigation District (IID), by far the largest user of Colorado River Water, to study water use and consumption within the valley as a means of identifying opportunities for water conservation. A report on water use patterns over a ten-year period has just been completed. This report should aid the Bureau of Reclamation in determining policies for water conservation and water allocations for the lower Colorado River. The source of water for the Salton Sea is primarily irrigation return flows, particularly from IID. The Salton Sea has numerous environmental problems, and congressional initiatives are currently being considered to try to solve these problems.

Terry Coffelt, Research Geneticist
Latex allergies are becoming a serious health problem. Guayule is a source of hypoallergenic natural rubber latex suitable for making medical products. ARS scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona in cooperation with scientists at the University of Arizona in Tucson, Arizona have publicly released five guayule advanced germplasm lines. With recent advances in processing of guayule latex, we anticipate that the commercialization of this new crop will occur in two to three years. These five lines will form the basis for varieties released to growers for the initial plantings. They grow faster and usually have higher latex contents than currently available germplasm. Higher yielding, faster growing, and easier to establish varieties are needed for the successful commercialization of guayule as a new crop.

David Dierig, Research Geneticist
New germplasm of *Lesquerella fendleri* to be released soon: Researchers at the U.S. Water Conservation Laboratory plan the public release of lesquerella germplasm with two important traits. *Lesquerella* species are native to the U.S and have potential as a new industrial oilseed crop, similar to imported castor. The hydroxy fatty acids found in their seeds can be used in cosmetics, lubricants, paints and coatings, and plastics and nylons. Gums from the seed coat are valuable for consumer products, cosmetics and oil drilling. The seed-coat of one of the released

lines is yellow compared to brown of the wild type. Oil from this seed has less pigmentation, especially important for the cosmetic industry. The flowers of the other line to be released do not produce pollen (male sterile) and could benefit plant breeders for use in hybrid seed production. These new releases could lead to more diverse crops for the American farmer and a larger industrial market for U.S. industry. Cultivation of lesquerella could reestablish industrial activity in the U.S. for processing and derivatization of hydroxylated oils.

Douglas J. Hunsaker, Agricultural Engineer

Studies on cotton water use by researchers at the U. S. Water Conservation Laboratory in Phoenix, Arizona, have quantified the amount of soil evaporation that occurs during irrigation events, an aspect presently neglected in determining state water duties. The studies show that the amount of water loss from soil evaporation constitutes as much as 15% of the total crop water use. Cotton farmers are generally unable to meet the target irrigation efficiency of 85%, which is difficult to achieve even when considering the quantity of water that evaporates from the soil. The study results should assist farmers and the Arizona Department of Water Resources in their negotiations on future water duties.

Sherwood B. Idso, Research Physicist

Research conducted at the U.S. Water Conservation Laboratory over the past few years has led to the development of a simple and inexpensive technique for assessing the biological consequences of increases in the air's carbon dioxide concentration for both terrestrial and aquatic plants. This "poor man's biosphere" approach to global change experimentation has been tested successfully in an honors botany high school class, an eighth-grade general science class, and a fifth-grade class at an elementary school of the Salt River Pima-Maricopa Indian Community. The three levels of complexity of the program have all proved adequate for their purposes. At the high school, the experimental program was the basis for the honors botany class entry in a statewide science project competition that won the participants first place in the state and a $10,000 award for science enrichment activities. In fact, the project was deemed so outstanding with respect to all other entrants that the judges refused to award any second or third place prizes! Work is in progress to make the experimental program available to teachers and students worldwide via scientific and educational publications and programs.

Benjamin Kaufman, Research Geneticist

The first molecular genetic study of *Lesquerella fendleri*, a new industrial crop that has evoked interest for its unique oil and hydroxy fatty acid, is being completed at the USDA-ARS U. S. Water Conservation Laboratory in Phoenix. Because emasculation is one of the most costly and labor intensive components of hybrid seed production, the objective is to develop the ability to introduce male sterility as a substitute for emasculation, into elite germplasm. After screening a sample of male sterile plants and male fertile plants with 100 molecular markers, 10 markers were identified as potentially diagnostic of the plant fertility state. These results currently are being confirmed with a larger sample. The utilization of these markers to screen desired lines for the plant fertility trait will be a significant step toward commercialization of *L. fendleri*.

Bruce A. Kimball, Research Leader
Rising CO_2 decreases wheat water requirements slightly. The carbon dioxide (CO_2) concentration of the atmosphere is increasing, which may affect the water requirements of wheat and other plants in the future. In order to determine the effects of such elevated levels of CO_2 on plant water use (as well as growth, yield, soil carbon storage, and other parameters), four experiments were conducted by scientists from the USDA-ARS, U.S. Water Conservation Laboratory and colleagues from the University of Arizona and other institutions on field-grown wheat at ample levels of water and fertilizer. Using the free-air CO_2 enrichment (FACE) technique, the air over the open field plots was enriched with CO_2 by 200 ppm above today's ambient, such as expected near the middle of the next century. The FACE treatment increased the wheat canopy temperature about 0.6°C (1.1°F), which could cause optimum areas for wheat production to shift poleward in the future. Daily water use was consistently lower in the FACE plots by about 6.7%, which suggests that wheat water requirements should decrease slightly in the future, provided any accompanying changes in climate are not too adverse.

Bruce A. Kimball, Research Leader
Bruce Kimball and Paul Pinter, scientists at the U.S. Water Conservation Laboratory in Phoenix, Arizona, attended the fifth meeting of the GCTE Wheat Network in Potsdam, Germany on 16-19 November 1998, where testing of several wheat growth models against Arizona FACE (free-air CO2 enrichment) Wheat Datasets was one of the primary activities. This Network was created under the auspices of the IGBP-GCTE (International Geosphere-Biosphere Programme, Global Change Terrestrial Ecosystems) Focus 3: Agriculture; A3.1, Experiments on Key Crops. It consists of about 10 active wheat experimentalists and about 10 wheat modelers who are trying to develop wheat models capable of predicting the effects of the increasing atmospheric CO2 concentration and any concomitant climate change on future wheat productivity. Lacking walls, FACE produces an environment as representative of future fields as is possible today. Two FACE Wheat experiments were conducted from December-May in 1992-3 and 1993-4 at ample and limited soil moisture, and another two were conducted in 1995-6 and 1996-7 at ample and limited soil nitrogen. Scientists from the USDA-ARS U.S. Water Conservation Laboratory and the University of Arizona were major participants. Because the growth data were obtained at frequent intervals through the growing season, and because many needed ancillary measurements were made, these data were especially valuable for the validation process for both present and future CO2 conditions. Indeed, the performance of each model in terms of its ability to simulate two of the Arizona FACE Wheat datasets (as well as some others) is being made a part of the GCTE Wheat Network Metafile record of each registered wheat model.

Francis S. Nakayama, Research Chemist
Scientists at the U.S. Water Conservation Laboratory in Phoenix, Arizona, in cooperation with the Forest Products Research Laboratory in Madison, Wisconsin, have fabricated particle board from guayule bagasse. The large quantities of waste bagasse formed as a result of commercial extraction of hypo-allergenic rubber latex from the guayule shrub would be the raw material for this particle board production. Use of the bagasse will automatically solve the environmental of how to dispose of the bagasse. In addition, preliminary economic analysis indicates that this byproduct can compete with board made of other types of raw materials. Physical and biological tests are underway to determine the properties of various treatment combinations and to optimize the fabrication process.

Paul J. Pinter Jr., Research Biologist

Elevated levels of atmospheric CO_2, such as those projected to occur globally by the middle of the 21st century, stimulated grain yields of wheat by about 16% under conditions of ample soil nitrogen, whereas the increase was about 8% when soil nitrogen was low. Although the specter of future crop failures due to global warming caused by increasing atmospheric CO_2 concentration exists, these results suggest that the direct effects of higher CO_2 on wheat yields will partially mitigate adverse effects of climatic changes. These results were obtained using a technique called free-air CO_2 enrichment (FACE) whereby the air above open-field plots near Maricopa, Arizona, was enriched with CO_2 to about 560 ppm (200 ppm above ambient). Obtained by researchers at the USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, AZ, and their colleagues at the University of Arizona and elsewhere, these results suggest that the increasing atmospheric CO_2 concentration will be of the most benefit to growers who apply adequate nitrogen fertilizer, whereas the benefit will be smaller for farmers in developing countries and natural ecosystems where soil fertility is low.

Paul J. Pinter Jr., Research Biologist

Elevated levels of atmospheric CO_2, increased the amount of solar radiation captured by grain sorghum plants for use in photosynthesis and caused the crop canopy to cover the ground earlier. These results were obtained using a technique called free-air CO_2 enrichment (FACE) whereby the air above open-field plots was enriched with CO_2 to a concentration expected to occur by the middle of the next century. Unlike glasshouse experiments where most of this research has been conducted in the past, FACE exposes plants to natural levels of light, water, and nutrients and produces results that are more applicable to production agriculture. The FACE sorghum project (begun in July 1998) is the third in a series of multi-year experiments studying the effects of global change on important food and fiber crops. Previous experiments with cotton and wheat have also shown beneficial effects of elevated CO_2 on early season canopy development. This research was conducted near Maricopa, Arizona, by plant and soil scientists at the USDA, ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona, and their colleagues at the University of Arizona in Tucson.

Theodor Strelkoff, Research Hydraulic Engineer

User-Friendly Surface Irrigation Simulation Software (SRFR) Released: After many months of exchanges with cooperators who had been receiving beta-test versions, SRFR was formally released in May of this year. The principle aim of the software is to provide quick responses to a variety of what-if scenarios that can be proposed by field advisors, consultants, extension personnel, etc., to assist in the development of recommendations for water-saving, high-efficiency surface irrigation with the methods suitable for their geographical area. A leading cooperator, the Natural Resources Conservation Service, made its web site available to the general public for downloading the software. A wide variety of surface-irrigation techniques and scenarios can be simulated with this menu-driven graphics-oriented program – surge flow (featuring a variety of simulated commercial surge valves), level basins with drainback, cablegation, cutback inflows, the effects of badly graded fields, or soils with varying infiltration characteristics along the length of run, to name a few. The animated and post-irrigation graphical output is also of educational value in irrigation training courses. And, in a nontraditional, hydrologic application, the program is being used to help design border filter strips aimed at reducing the sediment load of storm runoff passing through agricultural lands into waterways.

Gerard W. Wall, Plant Physiologist

Researchers at the U.S. Water Conservation Laboratory in Phoenix, Arizona, have shown that elevated carbon dioxide (CO_2), such as is expected in the 21st century, is advantageous for the root system of a wheat crop and consequently, for grain production. Because the atmospheric CO_2 is expected to rise throughout the next century, this work addresses the need to determine if this change in global climate would impact wheat production, the world's foremost grain supply. Scientists investigated the relationship between atmospheric CO_2 and net production by exposing a wheat crop in an open field to about double the amount of CO_2 presently in the earth's atmosphere. The root system of the crop showed an increase in branching, surface area, and thickness for all growth phases, and the effect was more pronounced under water stress compared with a well-watered crop. This CO_2-induced enhancement in root growth was accompanied by a 10 percent increase in yield under well-watered conditions and a 20 percent increase under water-stressed conditions.

U. S. WATER CONSERVATION LABORATORY SUPPORT STAFF

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Alexander, William L.	Agronomist
Arterberry, Carl K.	Agricultural Science Research Technician/Soils
Askins, JoAnne	Physical Science Technician
Barnes, Edward M.	Agricultural Engineer
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Lab Director, Research Leader and Research Hyd. Engineer
Coffelt, Terry A.	Research Geneticist (Plants)
Colbert, Sharette M.	Physical Science Technician
Corris, Virginia D.	Office Automation Assistant
Dahlquist, Gail H.	Agricultural Science Research Technician/Plants
Dierig, David A.	Research Geneticist (Plants)
Draper, T. Lou	Secretary (Office Automation)
Gerard, Robert J.	Laboratory Support Worker
Gerszewski, Susette M.	Biological Science Technician/Plants
Harner, Paulina A.	Secretary (Office Automation)
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Johnson, Kathy J.	Physical Science Technician
Johnson, Stephanie M.	Biological Science Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
LaMorte, Robert L.	Civil Engineer
Leake, Greg S.	Biological Science Technician/Plants
Lewis, Clarence L.	Machinist
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Specialist
Moran, M. Susan	Research Physical Scientist
Nakayama, Francis S.	Research Chemist
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Powers, Donald E.	Physical Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rish, Shirley A.	Program Analyst
Rokey, Ric R.	Biological Science Technician/Plants
Strand, Robert J.	Engineering Technician
Vinyard, Stephen H.	Physical Science Technician
Wahlin, Brian T.	Civil Engineer
Wall, Gerard W.	Plant Physiologist

ADMINISTRATIVE OFFICE

Name	Title
Albright, Dixie D.	Safety and Occupational Health Manager
Hodge, Vanessa J.	Budget and Accounting Assistant
Johnson, Richard E.	Office Automation Assistant
Lee, Richard E.	Custodial Worker
McDonnell, Guy C.	Physical Science Aid
Martin, Kevin R.	Air Cond. Equipment Mechanic
Sexton, Judith A.	Purchasing Agent
Wiggett, Michael R.	Administrative Officer

TEMPORARY EMPLOYEES

Name	Title
Adam, Neal R.	Plant Physiologist
Bautista, Eduardo	Agricultural Engineer-
Bross, Monique T.	Physical Science Technician
Bryant, Ross	Biological Science Technician
Conley, Matthew M.	Biological Science Technician/Plants
Eggemeyer, Kathleen D.	Biological Science Technician
Eshelman, Trathferd G.	Science Technician
Gardner, Scott D.	Publications Clerk
Gilbert, Kathleen	Biological Science Aid
Helfert, Michael	Biological Science Technician
Holifield, Chandra D.	Biological Technician
Kaiser, Aaron R.	Biological Science Aid
Luna, Traci E.	Biological Science Aid
Morgan, Stefani K.	Office Automation Clerk
Oliveri, Jose L.	Biological Science Technician
Olivieri, Laura M.	Biological Science Technician
Triggs, Jonathan M.	Biological Science Aid
Waichulatis, Steve R.	Biological Science Aid

TEMPORARY STATE EMPLOYEES

Baker, Michael G.	Research Specialist-Staff
Brooks, Talbot J.	Research Technician
Lewis, Laurie A.	Senior Machinist/Staff
O'Brien, Carrie C.	Research Laboratory Assistant-Staff
Pabian, David J.	Associate Engineer/FACE
Richards, Stacy	Biological Science Aid
Schmidt, Baron V.	Computer Programmer Assistant
Strelkoff, Fedja	Research Hydraulic Engineer/Research Professor (U of A)
Tomasi, Pernell M.	Research Laboratory Assistant

COOPERATORS

UNIVERSITIES

Arizona State University	Tempe, Arizona
Department of Geography	
Department of Plant Biology	
California Polytechnic State University	San Luis Obispo, California
Colorado State University	Fort Collins, Colorado
Delft Technical University	Delft, The Netherlands
Humbolt University	Berlin, Germany
Kansas State University	Manhattan, Kansas
Loughborough University	England
New Mexico State University	Las Cruces, New Mexico
Northern Arizona University	Flagstaff, Arizona
Northwest Agriculture University	Yangling, Shaanxi, China.
Oregon State University	Corvallis/Medford, Oregon
Texas A&M University	Lubbock/Pecos, Texas
Agriculture Experiment Station	
Universidad Autonoma Agraria Antonio Narro	Saltillo, Coahuila, Mexico
Universidad de Cordoba	Cordoba, Spain
Universita della Tuscia	Viterbo, Italy
Universitat Autonoma	Barcelona, Spain
University of Akron	Akron, Ohio
Department of Chemistry	
University of Alberta	Edmonton, Alberta, Canada
University of Arizona	Tucson, Arizona
College of Agriculture	
Cooperative Extension	
Dept of Agri & Biosystems Engineering	
Dept of Hydrology and Water Resources	
Dept of Plant Sciences	
Dept of Soil, Water & Env Science	
Marana Agriculture Center	Marana, Arizona
Maricopa Agriculture Center	Maricopa, Arizona
Office of Arid Land Studies	
Safford Agriculture Center	Safford, Arizona
University of California	Riverside, California
University of Essex	Colchester, United Kingdom
University of Florida	Gainesville, Florida
University of Guelph	Guelph, Ontario, Canada
University of Idaho	Moscow, Idaho
University of Illinois	Chicago, Illinois
Natural Resources and Environmental Sciences	Urbana, Illinois

University of Michigan	Ann Arbor, Michigan
University of Nebraska	Lincoln, Nebraska
University of North Dakota	Fargo, North Dakota
University of Wisconsin	Madison, Wisconsin
Utah State University	Logan, Utah
Virginia Tech University	Blacksbury/Suffolk, Virginia
Vrie Universiteit of Amsterdam	Amsterdam, Netherlands

STATE, COUNTY, AND CITY AGENCIES

Arizona Department of Agriculture	Phoenix, Arizona
Arizona Department of Environmental Quality	Phoenix / Tucson, Arizona
Arizona Department of Water Resources	Phoenix, Arizona
Idaho National Engineering and Environmental Laboratory	Idaho Falls, Idaho
Irrigation Management Service	Casa Grande, Arizona
Maricopa County Environmental Services Department	Phoenix, Arizona
Pinal County Air Quality Control District	Florence, Arizona
The City of Surprise	Surprise, Arizona
West Pinal Natural Resource Conservation District	Casa Grande, Arizona
Atmospheric & Climate Research Division	

FEDERAL AGENCIES

Central Arizona Water Conservation District	Phoenix, Arizona
Coastal Plain Experiment Station	Tiffton, Georgia
Farm Service Agency	Casa Grande, Arizona
NASA Goddard Institute for Space Studies	New York, New York
NASA Goddard Space Flight Center	Greenbelt, Maryland
NASA Stennis Space Center	Mississippi
National Germplasm Resources Laboratory	Beltsville, Maryland
Natural Resources Conservation Service	Portland, Oregon
National Water and Climate Center	
Oak Ridge National Laboratory	Oak Ridge, Tennessee
Office of Health and Environmental Research	Santee, California
U.S. Army Garrison	Fort Huachuca, Arizona
U.S. Department of Energy	Washington, DC
U.S. Salinity Laboratory	Riverside, California
USBR-Hydraulics Laboratory	Denver, Colorado
USDA-ARS Agronomy, Physiology, and Genetics Laboratory	Gainesville, Florida
USDA-ARS Air Quality Research Unit	Raleigh, North Carolina
USDA-ARS Grassland Protection Research	Temple, Texas
USDA-ARS Great Plains Systems Research	Ft. Collins, Colorado
USDA-ARS Hydrology Laboratory	Beltsville, Maryland
USDA-ARS National Center for Agricultural Utilization Res	Peoria, Illinois
USDA-ARS National Program Staff	Beltsville, Maryland

USDA-ARS National Soil Dynamics Laboratory	Auburn, Alabama
USDA-ARS Northwest Irrigation and Soils Res Laboratory	Kimberly, Idaho
USDA-ARS-Pacific West Area Office	Albany, California
USDA-ARS Southwest Watershed Research Center	Tucson, Arizona
USDA-ARS Water Management Research Lab	Fresno, California
USDA-ARS Western Regional Research Center	Albany, California
USDA-ARS Western Wheat Quality Laboratory	Pullman, Washington
USDA-Forest Products Laboratory	Madison, Wisconsin
USDI-U.S. Geological Survey	Sacramento, California

OTHER

Automata, Inc.	Grass Valley, California
Boeing Commercial Space Company	Seattle, Washington
Brookhaven National Laboratory	Upton, New York
Buckeye Irrigation District	Buckeye, Arizona
CDS Ag Industries	
CEMAGREF-Irrigation Division	Montpellier, France
Center for the Study of Carbon Dioxide and Global Change	Tempe, Arizona
Central Arizona Irrigation & Drainage District	Eloy, Arizona
Centre' d' Etudes Spatiales de la BIOspere	Toulouse, France
CSIRO Wildlife and Ecology	Lyneham, ACT, Australia
EMBRAPA/CPAC	Brazil
GeoSystems Inc.	Tucson, Arizona
Gila River Farms	Pinal County, Arizona
Global Water	Gold River, California
Institute for Biospheric Research	
Instituto de Agricultura Sostenible	Cordoba, Spain
Maricopa-Stanfield Irrigation & Drainage District	Stanfield, Arizona
McKemy Middle School	Tempe, Arizona
National Institute of Agro-Environmental Sciences	Tsukuba, Japan
Plant Germplasm Introduction Station	Pullman, Washington
Plasti-Fab	Tualatin, Oregon
Potsdam Institute for Climate Impact Research	Potsdam, Germany
RESOURCE21	Englewood, Colorado
Salt River Project	Phoenix, Arizona
Salt River Elementary School	Salt River Pima-Maricopa Indian Community
Tempe Elementary School District	Tempe, Arizona
Tempe Union High School District	Tempe, Arizona
Tempe High School	
Valmont Industries	Valley, Nebraska
Victor Ruiz, IMTA	Cuernavaca, Mexico
Wellton-Mohawk Irrigation & Drainage District	Wellton, Arizona
Yulex Corporation	Philadelphia, Pennsylvania